# What's the matter?
## Toward a neo-Aristotelian Ontology of Nature

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*This thesis is submitted for the degree of Doctor of Philosophy.*

# Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution, except as declared in the Preface and specified in the text.

I wish further to state that no substantial part of my thesis has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge, or any other University, or any similar institution, except as declared in the Preface and specified in the text. This thesis does not exceed the prescribed word limit of 80,000 words for the Degree Committee of the Philosophy Faculty.

I also wish to note that Chapter 1 is based on my paper, 'Knowing nature', which is part of the anthology *Knowing Creation* (edited by A. B. Torrance, and T. H McCall), and was submitted during the course of this doctorate. Sections 4.3–4.5 of Chapter 4 are based on my paper, 'What's the matter with Super-Humeanism?', published by *The British Journal for the Philosophy of Science*, which was also submitted during the course of this doctorate. Chapter 6 is based on my paper, 'Cosmic power monism', which is about to be submitted to *The European Journal for the Philosophy of Science*.

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# Abstract

This thesis contributes to the development of a 'neo-Aristotelian' ontology of powers that accommodates quantum phenomena. It offers a number of philosophical objections to 'Super-Humean' metaphysics, and constructs a sequence of models that aim to improve upon it, using the metaphysical toolbox constructed in Part I.

In Part II, I explore how quantum entanglement challenges the 'classical' conception of the world as consisting of particles (or fields) with intrinsic physical properties (Chapter 3). I consider the metaphysical model offered by Super-Humeanism, which accommodates entanglement by combining a 'primitive ontology approach' to quantum mechanics with ontic structural realism (Chapter 4). According to Super-Humeans, the world is made of matter points constituted by distance relations. I raise three objections to its structuralist conception of matter. I then propose an alternative semi-Humean model, 'Bohmian power structuralism', which overcomes these objections through an ontology of 'power-atoms' with multi-track causal powers (Chapter 5). But its Humean conception of laws can be challenged. A second model, 'power monism', enriches the primitive ontology to include a 'cosmic power' that transforms the power-atoms into a cosmic whole, and supports an Aristotelian-essentialist conception of laws (Chapter 6). This model overcomes the difficulties with power structuralism, but is susceptible to Hawthorne's 'extrinsicality' argument, excluding consciousness from the physical world.

In Part III, I consider the emergence of thermochemical properties within macroscopic (or mesoscopic) quantum systems. Metaphysical models that incorporate only finite degrees of freedom, like Super-Humeanism, cannot accommodate intrinsic properties like temperature and chemical entropy, which are represented in physics in the 'thermodynamic limit' (Chapter 7). I offer an additional argument against adopting a reductionist approach based on Putnam's 'permutation argument' (Chapter 8). Finally, I outline a third model, 'power pluralism', in which the world consists of: a substrate of 'power-gunk', and 'substantial powers' that elicit substances from the power-gunk (Chapter 9). In this model, quantum-entangled microscopic particles are potential parts of macroscopic (or mesoscopic) substances, which have intrinsic thermochemical properties.

In memoriam patris,

Anthony Peter Simpson
1948 – 2009.

# Contents

# What's the matter?

*The matter of Aristotle, which is mere potentia, should be compared to our concept of energy, which gets into actuality by means of the form.*

– Werner Heisenburg, *Physics and Philosophy*

# Acknowledgements

*In all circumstances give thanks, for this is the will of God*

– St Paul of Tarsus, *1 Thessalonians*

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# Part I

# Powers and grounding

Chapter 1

# Nature and the old Aristotelianism

*The fact, however, that there was this misunderstanding and misuse of the substantial forms should not bring us to throw away something whose recognition is so necessary in metaphysics.*

– Leibniz, *Discourse on Metaphysics*

## §1.1. Hylomorphism

What is the world made of? If it is made out of something, then are there *many* things, or is there really just *one* thing, from which everything else is made? If there are many things, what unites those different things to make one world, and how should we account for how they change?[1]

Philosophical questions about the nature of matter and the possibility of change did not begin with the 'scientific revolution' of the seventeenth century, nor with the advent of 'modern philosophy'. In fact, in seeking to make sense of contemporary quantum mechanics, both pioneering physicists, like Werner Heisenburg, and modern philosophers of science, like Nancy Cartwright, have found themselves reaching as far back as the metaphysics of Aristotle for inspiration, whose philosophy was shaped in turn by Plato and the musings of the pre-Socratics.[2]

The degree to which Nancy Cartwright's philosophy of science, with its appeal to 'Aristotelian powers',[3] or anything that I shall propose in this thesis, represents an authentic recovery of any part of Aristotle's philosophy of nature, is something I must leave to others to decide. I take my thesis to be an exercise in metaphysics and the philosophy of science, rather than a treatise on ancient philosophy. Nonetheless, I have found myself turning toward parts of Aristotle's metaphysics, or at least toward metaphysicians who have studied his works more deeply than I have, in order to grapple with some of the problems raised by the 'quantum revolution' in physics that I shall expound in due course. The inoculation that I received against Aristotle during the course of my own training in physics, however, and the general lack of interest in medieval philosophy among analytic philosophers, leaves me compelled to give some account of why I have begun reconsidering certain much maligned 'Aristotelian' ideas, like the doctrine of hylomorphism, which strongly influenced the course of Western philosophy via the reception of Aristotle in the Middle Ages.

Although the philosophy of the Middle Ages was far from monolithic, medieval metaphysics from the thirteenth century can be broadly characterised within the Latin tradition by its explicit commitment to the Aristotelian principles of 'matter' (*hyle*) and 'form' (*morphe*). (The term 'hylomorphism' is a portmanteau of these Greek words.) Aristotle's hylomorphic doctrine of substances deploys matter and form as co-relative concepts to explain how the world is carved into fundamental substances with intrinsic properties that persist through time. Among some scholastic philosophers, the matter of a substance was conceived as a determinable substrate underlying all change, and forms were conceived as different determinations of matter which fixed their causal powers. Among others, they were understood differently.

However, whilst Aristotle's doctrine of hylomorphism came to be interpreted in various ways, some of which I shall touch upon in this chapter, it continued to frame philosophical debate until the rise of *corpuscularianism* in the seventeenth century. Strict demarcations between medieval and early modern philosophy are increasingly discouraged by historians of philosophy. Nonetheless, the wide-spread rejection of form as the determining principle of matter,[4] initiated by the early mechanistic philosophers, and led by René Descartes and John Locke, constitutes a striking discontinuity between medieval and modern notions of the natural order. Indeed, it has often been presented as one of the lasting and inevitable triumphs of modern science, in which an opaque medieval philosophy was forced into retreat by a more perspicuous account of nature.

My thesis aims to put such hackneyed claims into question, by drawing upon hylomorphic ideas to make sense of contemporary physics at precisely those points where the ghosts of corpuscularianism, so to speak, seem to be inhibiting understanding.[5] More immediately, I wish to suggest a different philosophical evaluation of the demise of substantial form. In assessing the merits of Aristotle's doctrine, I believe we should distinguish between two general approaches that I shall call *Aristotelian-Thomistic* and *late scholastic* [Simpson, 2018].[6] I claim that, in doing so, it is plausible that the widespread rejection of form, which continues to this present day, is an historical contingency: it results in part from the 'physicalisation' of Aristotelian-Thomistic hylomorphism in late scholastic metaphysics, combined with the rise of a kind of microphysical reductionism which (I shall later argue) contemporary physics does not support.

In offering these observations, I hope to persuade the reader that it is not unreasonable to draw upon hylomorphism for inspiration, in spite of the 'bad press' it received in the seventeenth century. However, since I am neither a classicist nor a medievalist, and primarily concerned with the metaphysics of science, the reflections offered in this introductory chapter shall be brief and painted with a broad brush. My goal in this thesis is to work towards uncovering an ontology that is compatible with quantum mechanics and accommodates the possibility of scientific inquiry. Any rigorous examination has been deferred to subsequent chapters.

## §1.2. Proto-scientific inquiry

Although Aristotle was famously the protégé of Plato, and both philosophers aspired to universal truths about reality, it is widely acknowledged that these great thinkers of antiquity diverged in their methodology and their metaphysics.[7] For Plato, reality lay beyond our experience of particular things, in a transcendent realm of universals he called the 'forms', which somehow cause the plurality of particulars with which we are acquainted, and in which these various particulars are said to 'participate'. A form is the universal essence which bestows qualitative similarity upon particular things – such as the form of the triangle, or the form of man – and can only be known through a kind of recollection (see eg. [Plato, Meno, 71-81, 85-86]).[8]

In his treatise, *On Generation and Corruption*, Aristotle criticised Plato's treatment of the forms on the grounds that, since they are transcendent entities, they cannot function as efficient causes in the world of space and time [Aristotle, Gen. & Corr. 335b, 18-24]. For Aristotle, if the forms are to explain the characteristic activities of concrete particulars, they must somehow be 'immanent' within the 'substances' that they are said to 'in-form'. Moreover, according to Aristotle, we ultimately come to know the forms through sensory experience, by causally interacting with substances, rather than through recollection [Aristotle, Metaphysics III 3-4]. It is the substances, not the forms, that act as efficient causes in nature.

Whilst the ontological status of the forms in Aristotle's metaphysics, and their relation to the substances that they are said to in-form, is still vigorously debated (of which more later), Aristotle maintained a robust commitment to the reality of in-formed substances that exist in the world of space and time. This broadly empirical stance is manifest in Aristotle's systematic study of natural phenomena and his indefatigable classification of the natural world into natural kinds. For Aristotle, philosophical inquiry into the truth about the world began with the study of nature as it presents itself in ordinary experience, proceeding to more abstract reflections upon the nature of time and change (in the *Physics*), and thence to more fundamental questions about the nature of being (in the *Metaphysics*).

For these reasons, I suggest, it is not unreasonable to consider Aristotle as a kind of proto-scientist who inaugurated the empirical tradition of scientific inquiry; a tradition characterised by a certain confidence in the power of human reason to uncover the truths about nature. For Aristotle, the truths about nature ultimately pertain to the various forms that are immanent within the world of change.

## §1.3. Matter and form in Aristotle

### i. *Being and change*

Aristotle distinguished two ways of being in his account of change: there is *being-in-potency* (or potentiality) and there is *being-in-act* (or actuality) (see [Aristotle, Physics I.7]).[9] According to Aristotle, as he has generally been understood,[10] the natural order is fundamentally composed of *substances*, which are concrete particulars that have *powers* to bring about change. For example, animals are organic substances which exercise powers of growth and nutrition.[11] Yet animals are not permanent entities which can persist through all kinds of change. Rather, organic substances are transitory entities that come into being through the procreative activities of other substances, and they are subject to processes of death and decay.

Aristotle introduced the co-relative concepts of *matter* (hyle) and *form* (morphe) in his account of how substances are generated and decomposed in nature, and how they take on different characteristics during the course of their existence (see eg. [Aristotle, Physics II.3]). Matter is that which changes and gets determined (or actualised), and form is that which determines (or actualises) matter. Both metaphysical principles are required to explain the changes in nature that we observe in ordinary experience, along with the concept of privation, which is the lack of the form that is required by whatever the goal of the change happens to be.

For instance, when an animal consumes a plant, by exercising its powers of growth and nutrition, it transforms the matter of the plant into its own flesh. In so doing, the substance of the animal is a subject of change: by gathering flesh where there was previously a privation, the matter of the substance is determined by a different *accidental form*. In exercising its power to nourish, and in being consumed by the animal, the matter of the plant is also a subject of change. By being transformed into the flesh of the animal, it is stripped of powers that are essential to the nature of the plant, and acquires powers that are essential to the nature of the animal. In this case, the matter is now said to be determined (or actualised) by the *substantial form* of the animal, since the animal exists where its form was previously in privation. The causal relations between two substances are described in terms of their powers to effect change, whether the change brought about is accidental or substantial in kind.

### ii. *Actual and potential parts*

Aristotelian substances have a *per se unity* which other kinds of entities lack. In order to distinguish an Aristotelian substance, like an animal, from an aggregate, like a pile of sand, we must distinguish between *actual* and *potential* physical parts. An aggregate is composed of actual physical parts that have a determinate physical nature. These parts can in principle exist independently of the whole, and retain their natures and identities even whilst they are composing an aggregate. An aggregate entity derives its nature and being from the sum of its actual parts.

An Aristotelian substance, by contrast, does not consist of actual physical parts into which it can (hypothetically) be decomposed. Rather, all the physical parts of a substance are dependent for their physical natures upon the substance of which they are part. Whilst a living substance, such as an animal, can decompose into a collection of non-living chemicals, which do not depend upon the original substance for their existence or physical natures, these physical entities are not *numerically identical* to any of the parts of the substance that existed prior to its decomposition. The separate entities into which a substance may decompose on corruption are said to exist only in *potential*, just so long as the substance itself exists.[12] The metaphysical unity of the substance thus pertains to its having a single nature, upon which the natures of all of the parts of the substance jointly depend. It is the metaphysical unity of the substance that distinguishes it from an aggregate.[13]

It is possible to make this distinction more precise. According to Miller, actual and potential parts satisfy the ordering axioms of classical mereology, inasmuch as the classical definitions of 'proper parthood', 'overlap', 'underlap', and 'disjointness' can be applied without modification [Miller, 2019]. However, potential parts do not satisfy the classical axiomatisation for *decomposition*. Following the classical remainder axiom, or the alternative axioms of strong and weak supplementation, if $x$ is a proper part of $y$ there must be some other part of $y$ that is *disjoint* with $x$ [Cotnoir & Varzi, forthcoming, pp. 25, 104, 111]. Miller proposes that the appropriate decomposition axiom for potential parts is what Cotnoir and Varzi have called the axiom of 'strong company' instead: namely, for all $x$ and $y$, if $y$ is a proper part of $x$, then there exists a further part which is a proper part of $x$ and not a part of $y$ [p. 125]. In this model, a substance, unlike an aggregate, is without disjoint parts.

### iii. *Aristotelian-Thomistic hylomorphism*

In this brief exposition, three propositions that characterise what I shall call the *Aristotelian-Thomistic* doctrine of hylomorphism can be discerned which were subsequently challenged during the rise of corpuscularianism. First:

> *Efficient and final causes*
> AH/I: The existence of substances with causal powers to bring about change explains the different phenomena that we observe within the physical world.

A substance $X$ brings about some change $\phi$ in another substance $Y$ by exercising an *active* power to change $Y$, whilst the other substance $Y$ suffers the change brought about by $X$ by exercising a *passive* power. There is an intentional or 'teleological' aspect to the nature of this interaction: the substance $X$ is said to have a power $P$ *to* bring about $\phi$, which is as much as to say that the power $P$ is *directed* toward $\phi$.[14] Both the agent and the recipient act as efficient causes only by co-manifesting their 'reciprocal' causal powers. Yet substantial forms, according to Aristotle, also have a role to play in explaining the physical nature of substances:

*Formal and material causes*
AH/II: The existence of substantial forms explains how the potentiality of matter is determined (or actualised) as different substances with causal powers.

For Aristotle, animals have powers of perception, locomotion, and various passions, that plants do not, and humans have rational (or, intellectual) powers that other animals do not. Since animal and human substances are transitory, however, and do not have actual physical parts, we require an explanation of how different kinds of substances arise in the physical world. According to Aquinas' interpretation of Aristotle, the fact that there are substances in the world with fundamentally different causal powers is explained by the existence of different substantial forms, which determine their matter in different ways [Aquinas, De Principis Naturae 5]. I suggest, then, that the fundamental explanatory roles of matter and form can only be robustly distinguished if we accept the following proposition:

*Anti-physicalist principle*
AH/III: The physical parts of a particular substance do not have a determinate (or actual) physical nature apart from the form of the substance.

Matter and form are co-relative principles, according to Aristotle's doctrine of hylomorphism: the matter of a particular substance has no causal powers to act in the world, apart from the form of the substance, and the form of the substance has no causal power to act in the world, apart from the matter whose causal powers it determines. Hence a substance cannot consist of actual physical parts that have their own essential and intrinsic powers, which interact with one another as efficient causes. The question of whether or not matter has *any* being apart from the existence of *substances*, however, and whether or not forms have *any* being apart from the substances they in-form, is a historical controversy of long-standing.

According to a traditional line of interpretation that is often attributed to Aquinas, Aristotle thinks of substantial form as *both* the principle of unity of a substance *and* that by which substances are fundamentally and objectively *what* they are [Aquinas, De Principis Naturae, 5, 30]. For Aquinas, whilst a substantial form is not a constituent part of a substance, in the way that the material elements of a substance are parts of the substance, a substantial form may be said to *unite* itself to the matter of a substance in virtue of being the *formal cause* of its essence or nature [Aquinas, De Ente et Essentia, 6].[15] In Aquinas's view, substantial forms play a role in objectively carving the world into different substances, and must therefore have being apart from the substances that they in-form.

According to a more recent line of interpretation that originates in the work of Theodore Scaltsas, however, matter and form for Aristotle are merely *abstractions* from the fundamental unity of the substance, and have no being apart from the substance from which they are abstracted [Scaltsas, 1994]. For Marmodoro, for example, whilst the substantial form is the principle of *unity* of the substance, it is not objectively the *cause* of the substance being *what* it is [Marmodoro, 2013a].[16] Rather, the matter and form of a substance are related to the unified whole as *constituent principles*, rather than *constituent parts*, which we subjectively depend upon to carve nature according to our explanatory interests [Marmodoro, 2018b].[17]

I shall follow the older Aristotelian-Thomistic line of interpretation, in which a substance is counted as a unified metaphysical composite. Whilst I do not propose to settle this controversy in this chapter, or to engage in any detailed exegesis of Aristotle, I shall consider Marmodoro's approach to hylomorphism in Chapter 6, in the context of a contemporary metaphysical model, and will offer a number of reasons for rejecting it. (For detailed criticism of Scaltsas' line of interpretation, see [Peterson, 2018].) All I wish to claim here is that an 'Aristotelian' conception of hylomorphism, which distinguishes the explanatory roles of matter and form, will be one in which the anti-physicalist principle (AH/III) is staunchly maintained.

## §1.4. Matter and form in late scholasticism

Whilst the concepts of matter and form were widely deployed in scholastic metaphysics, in accounting for the nature and unity of substances, these doctrines were developed by some scholastic philosophers in ways that were incompatible with Aristotelian-Thomistic hylomorphism. No single systematic view characterises the late scholastic period. Nonetheless, it is possible to pick out some suggestive tendencies within medieval metaphysics that served as a prelude to corpuscularianism.[18]

I shall use the term *physicalise* to refer to the tendency to treat matter and form as having the same ontological standing as physical substances, or the actual parts of an aggregate, by regarding them as concrete entities with determinate causal powers.[19] The necessity of some material substrate underlying all forms of change was widely accepted within the Latin tradition. As Franco Burgersdijk observed, 'all seem to have granted to Aristotle that the generation and corruption of natural things requires a common subject'.[20] In this way, Aristotle sought to affirm the continuity of natural processes and to avert the supposition that change must involve creation from nothing.

However, the Aristotelian-Thomistic construal of this substrate as a *determinable potentiality*, which was defended by Aquinas, was widely criticised by other scholastics for failing to bottom out in anything concrete or determinate, and was never widely accepted, even in the thirteenth century. Duns Scotus, for example, insisted against Aquinas that this substrate should have actual parts.[21] William of Ockham, writing in the early fourteenth century, echoed Averroes in requiring that matter should have extension.[22] The metaphysical misgivings concerning a merely determinable substrate were starkly expressed by the seventeenth century Ockhamist, André Dabillon, who insisted that either 'the things that compose an actual being actually exist, or a substantial whole would be composed of nothing'. Since this position is untenable, he claimed that it must be the case that both 'matter and form are real substantial beings that exist actually in nature'.[23]

In addition to physicalising the material substrate of change, increasing its independence from substantial form, many scholastics seem to attribute a quasi-physical status to form, suggesting that it interacts with other entities like an efficient cause. A significant example of this tendency lies in the widespread rejection of the so-called 'unitarian doctrine' of substantial form.[24] In Aristotelian-Thomistic hylomorphism, a substance has a single substantial form, which is the principle of unity of the substance. For some scholastics, however, such as Scotus, a plurality of substantial forms were said to exist within the same substance. For example, the form of *corporeity* (by which an animal is embodied), and the form of the *soul* (by which an animal is living), were held to be present simultaneously within a human substance.

Yet if multiple substantial forms can exist within a substance that simultaneously determine its causal powers, wherein lies the unity of the substance? For certain scholastics, it seems the temptation was to preserve their commitment to the unifying character of forms by portraying them as elements within the composite with powers to *organise* their various parts into a single *functional whole*. Francisco Suárez, a philosopher of the late sixteenth and early seventeenth centuries, seems to be considering such a position when he writes, 'The aggregation of multiple faculties or accidental forms in a simple substantial subject is not enough for the constitution of a natural thing... A form is required that, as it were, rules over all those faculties and accidents, and is the source of all actions and natural motions of such a being.'[25] In this way, form becomes physicalised as something in the world with the causal power to organise other determinate parts within some kind of causal structure. This marks a departure from Aristotelian-Thomistic hylomorphism, I suggest, in which it is form that determines the causal powers of a substance.

Yet once matter and form have been physicalised, formal and efficient causation become difficult to distinguish from one another. For the Aristotelian-Thomistic hylomorphist, substances were supposed to share (in some sense) a common substrate of determinable potentiality, which is in-formed one way, and then another. For certain scholastics, however, substantial forms seem to act as efficient causes, since that is the only way in which they can make a causal difference to things that have their own essential and determinate natures. It is enough for my purposes to note that the meanings of the terms 'matter' and 'form' were modified in certain variants of scholastic hylomorphism. Whilst the metaphysical role of form, both in joint-carving and the generation of substance, remained the same in intention, the ways in which these tasks were implemented rapidly shifted from their Aristotelian-Thomistic moorings. Matter and form were physicalised, and formal causation confounded with efficient causation; a circumstance that would place the concept of substantial form in direct competition with scientific mechanisms.

## §1.5. Corpuscularianism

The mechanical philosophy of the seventeenth century, far from arising in a philosophical vacuum, represents a development in these tendencies, which culminated in the complete physicalisation of the substrate of change as material corpuscles with fully determinate properties, combined with an explicit rejection of the notion of substantial forms. Abandoning the hylomorphism of late scholasticism, the corpuscularists proposed an alternative ontology consisting of material bodies composed of determinate constituents arranged within physical space, echoing the atomism of Leucippus and Democritus that Aristotle had so vehemently opposed.

### i. *From potentiality to corpuscles*

One of the earliest instantiations of corpuscularianism was the mechanical philosophy of Descartes, who famously conjectured that reality could be neatly divided between thinking things (the 'res cogitantes') and extended things (the 'res extensa'), with the extended things being wholly characterised by the geometric properties of 'shape, size [and] position', and the mechanical property of the 'motion of particles of matter', which is governed by universal laws. A thorough-going reductionist in his approach to the material world, Descartes believed 'there is nothing in all of nature whose character (ratio) cannot be deduced through these same principles',[26] and dismissed substantial form as 'a philosophical being unknown to me'.[27]

It would be difficult to overstate the enduring impact of Descartes' metaphysics, although Cartesian physics was a short-lived affair by contrast: Isaac Newton rejected Descartes' identification of matter with extension, and proceeded to develop an alternative account of motion that would rapidly secure Newtonian mechanics as the archetype of modern physics. Nonetheless, the common commitment to corpuscles continued to set the agenda for natural philosophers from the seventeenth century. Buoyed by swift advances in the experimental sciences, corpuscularianism swiftly supplanted scholasticism in many parts of Europe, as scientists like Robert Boyle contrived plausible mechanical explanations for natural phenomena, specifically targeting cases in physics where scholastics had attributed phenomena to the activities of forms.[28] Henry Oldenburg, who served as the first secretary for the

Royal Society, memorably complimented Boyle for having ‘driven out that drivel of substantial forms’ which ‘has stopped the progress of true philosophy, and made the best of scholars not more knowing as to the nature of particular bodies than the meanest ploughmen’.[29]

### ii. *From substantial forms to universal laws*

Whilst corpuscularians maintained a commitment to the notion of a material substrate underlying all change – in Boyle’s view, a ‘substance extended, divisible, and impenetrable’ [30] – the doctrine of substantial forms was swiftly abandoned during the course of the seventeenth century (albeit with some notable dissenters, such as Leibniz [Leibniz, 1976]). This loss was accompanied by a shift in how change was conceived. As Silva observes: ‘intrinsic natural formal causes were replaced by extrinsically imposed laws of nature’ [Silva, 2019, p.65]. In a world stripped of substantial forms that determine the intrinsic powers of different substances that exist in nature, ‘natural philosophers needed to refer to the laws of nature that extrinsically guided the movements of corpuscles and atoms in a void’ [p.64]. According to Boyle, the material world that is laid bare by the physical sciences should be regarded as a ‘contrivance of brute matter managed by certain laws of local motion’ [Boyle, 2000, vol.10, p.447]. The corpuscularian matter, of which everything else is made, persists through time and only changes with respect to accidents like position. There is no need for the category of substantial change.

By the end of the eighteenth century, the French mechanist Pierre Simon de Laplace had given voice to a vision of a universal mechanism that would dominate the imagination of philosophers until the turn of the twentieth century – a cosmos whose state at any future time is entirely fixed by the present locations and momenta of small particles and the laws of Newtonian mechanics.[31] This is the world of ‘classical physics’, with which most philosophers are familiar, in which the universal laws of physics determine all the physical possibilities of nature. It is a world in which the substantial forms of the late scholastics – conceived as ‘organising powers’ – have no fundamental role to play in bringing about change.

### iii. *From laws and corpuscles to minds*

In spite of his role in undermining the old Aristotelianism, Descartes’ mind-body dualism has failed to sustain a significant following among modern philosophers, who have found the relation it posits between mind and body implausibly tenuous,[32] and often distance themselves from any explicit ontological commitment to ‘corpuscles’, preferring to describe the material world as containing ‘what a true complete physical science would say it contains’ [Crane and Mellor, 1990, p.186]. It became a matter of urgency to conceive of alternative ways in which the psychological world of the scientist might be related to the world that the scientist purports to describe.

The logical positivists of the early twentieth century, such as Schlick and Carnap, perceived their scientific empiricism as demanding some form of physicalism. Mid-century analytic philosophers, like J.C. Smart and U.T. Place, favoured a type of linguistic reductionism in which ordinary language ascriptions about the mind could be translated into true statements about our best physics. When syntactic explications of the mind-body relation fell into disfavour, philosophers searched for semantic explications instead. According to Donald Davidson, mental characteristics should be considered as 'supervenient' upon physical characteristics. This means that 'there cannot be two events alike in all physical respects but differing in some mental respect, or that an object cannot alter in some mental respect without altering in some physical respect' [Davidson, 2001, p.214].

Nonetheless, what animates both of these approaches, I suggest, is the ghost of a corpuscularian conception of matter: namely, that there is some substrate of determinate being underlying the macroscopic world of scientists and their experiments, whose laws and properties exist without further explanation. The philosopher's task is then to find the correct way of relating the 'mental' to these basic features. For example, Cian Dorr offers the following three-part recipe for constructing metaphysical hypotheses [Dorr, 2011, p.139], which has been described as 'orthodoxy for post-Quinean metaphysics' [Button, 2013, p.12]: first, a 'fundamental ontology' of physical constituents is to be stated; secondly, a 'fundamental ideology' should be specified to describe them; finally, 'some laws' must be laid down that 'capture important general patterns' among them [Dorr, 2011, p.139]. According to this procedure, the whole truth about the world supervenes upon the physical facts about these laws and constituents. I shall refer to this metaontology as *micro-monism*.

### iv. *The quantum revolution*

Let me lay my cards on the table. I have misgivings about the privileged status the micro-monist conception of nature continues to enjoy among analytic metaphysicians and philosophers of mind. I also share Leibniz's doubts about the wisdom of the corpuscularian philosophy that displaced the doctrine of hylomorphism, from which the philosophy of micro-monism descends [Leibniz, 1976]. My doubts and misgivings have arisen in the light of the quantum revolution, which overturned the universal pretensions of Newtonian mechanics in the 1920s, and with which contemporary metaphysicians and philosophers of mind are still coming to grips.

Specifically, I question whether a quantum mechanical description of nature supports an ontology of microphysical properties that stand without further explanation. I will recount this doubt in more detail in connection with the phenomenon of quantum entanglement, in which the quantum state of two microscopic systems that are quantum-entangled is *irreducible* to the quantum states of their separate constituents (see Part II). I also question whether the explanatory power of quantum mechanics is best enabled by reducing the physical possibilities of nature to different arrangements of a single set of microscopic constituents. I shall expound this doubt further in discussing the emergence of thermochemical phenomena in macroscopic quantum systems, such as phase transitions, which demand a plurality of *physically inequivalent* microscopic representations (see Part III). In the course of this thesis, I mean to call into question two micro-monist assumptions about nature:

*Matter with microscopic properties*
MM/I: There are fundamental microphysical properties, picked out by our 'best physics', which are intrinsic to the fundamental constituents of nature.

*Matter with microscopic constituents*
MM/II: Nature consists of a single set of microscopic constituents whose possible arrangements are determined by the laws of our 'best physics'.

In this thesis, I hope to take a few steps toward constructing a 'neo-Aristotelian' ontology of nature that dispenses with both of these micro-monist assumptions, beginning with metaphysical models that reject the first assumption (in Part II), and proceeding toward a model that rejects both assumptions (in Part III). I think a better description of nature can be achieved, which accommodates the phenomenon of quantum entanglement and the emergence of thermochemical phenomena, by deploying the ideas of metaphysical grounding and the metaphysics of potentiality that I shall discuss further in the following chapter (see Chapter 2), and which draws metaphysical inspiration from the Aristotelian doctrine of hylomorphism.

Although I am concerned with metaphysical models that affirm the possibility of scientific inquiry, and therefore the existence of scientists engaged in such inquiries, I have no intention of offering here an alternative philosophy of mind. Indeed, I suspect that a vast deal more work may be needed to transform our metaphysics of nature, in the light of the quantum revolution, before the construction of a satisfactory account of the mind's place in a 'post-corpuscularian' world becomes feasible. Yet if my criticisms of micro-monism are cogent, it may prove that the neglected Aristotelian-Thomistic doctrine of hylomorphism is ripe for rehabilitation.[33]

## §1.6. General remarks

In this chapter I revisited the Aristotelian-Thomistic doctrine of hylomorphism, in which substances are conceived as composites of matter and form, observing how it was 'physicalised' during the course of the Middle Ages and finally rejected in the seventeenth century in favour of the corpuscularian conception of matter. I noted the empirical motivations for Aristotle's conception of form (Section 1.2), and discussed how an Aristotelian-Thomistic implementation of hylomorphism should distinguish formal from efficient causation (Section 1.3). This distinction was subsequently undermined in later forms of hylomorphism (Section 1.4). Eventually, matter was conceived as an arrangement of corpuscules governed by universal laws, or simply whatever our best microphysical descriptions of the world tells us it is, and the concept of substantial form was dismissed as superfluous (Section 1.5). Nonetheless, the notion of a world that supports universal laws of nature does not necessarily exclude the Aristotelian-Thomistic concept of substantial form. In the following chapter, I shall lay out the metaphysical tools with which I will begin to formulate 'neo-Aristotelian' models that aim to accommodate quantum phenomena.

## Notes

[1]This chapter draws on a paper I completed and published during the course of my doctorate [Simpson, 2018]. Some paragraphs are taken from this paper verbatim.

[2]For a recent collection of essays concerning quantum physics and Aristotelian metaphysics, see [Simpson et al., 2017].

[3]For expositions of Cartwright's philosophy of science, see [Cartwright, 1999, Cartwright, 1994]. Concerning the need to return to 'Aristotelian powers', see [Cartwright and Pemberton, 2013].

[4]Wide-spread, but not universal: Leibniz was a notable exception.

[5]It is not unusual for prominent physicists to deny the intelligibility of quantum mechanics. Concerning the 'flight from reason' in physics, see [Dürr et al., 2012, chp.4].

[6]I shall be drawing particularly on historical studies by Robert Pasnau in [Pasnau, 2011].

[7]Famously, in Raphael's School of Athens, Plato is portrayed pointing a finger upward toward the sky, whilst one of Aristotle's hand is stretched toward the earth with his fingers splayed.

[8]For a discussion of universals in Plato and Aristotle, see [Scaltsas, 1994].

[9]In my references to Aristotle, I am relying upon [Barnes, 1984].

[10]For an alternative reading, in which Aristotle is fundamentally committed to *powers* (or power tropes), see [Marmodoro, 2014].

[11]That is, in virtue of their having animal forms, or souls.

[12]See eg. [Arist. Gen. & Corr. I.10] in [Barnes, 1984]; in particular, 327b23-b33. Also, [Arist. Metaphys. 1040b5-15 & 1040b5-15].

[13]For further discussion of integral wholes and potential parts, see [Simons, 2000, chp. 9]..

[14]The contemporary idiom of 'powers' is not the only way in which to think about the action of substances in Aristotle, but it is the most suitable way for my purposes.

[15]Koons suggests the following analogy: suppose we imagine a 3:4:5 right triangle. The imagined triangle is a compound that contains four things: my act of imagination, and each of the three lines. Clearly, the way in which my act of imagination is part of the imagined triangle differs from the way in which each of the imagined lines are parts of the triangle. Nonetheless, all four elements are distinct and disjoint parts of a whole.

[16]Marmodoro, following Theodore Scaltsas, considers substantial form to unify a substance by *re-identifying* the physical constituents from which it derives [Marmodoro, 2018b].

[17]Marmodoro suggests that, for Aristotle, the world consists fundamentally of 'power-tropes' that are characterised by our best physics [Marmodoro, 2014, Chp. 1].

[18]For a more detailed narrative about the physicalisation of matter and form, see [Pasnau, 2011].

[19]cf. Pasnau's discussion in [Pasnau, 2011].

[20][Burgersdijk, F. 1650, Collegium Physicum II.34, pp. 1314], as translated in [Pasnau, 2011].

[21]See [Scotus, Rep. II.12.2 n. 7 (XI:322b)] in [Wolter and Bychkov, 2004].

[22]For a discussion of Ockham's view, see [Pasnau, 2011], 'Matter and extension'.

[23]See [Dabillon 1643, Physique I. 3.2, p. 103] as cited in [Pasnau, 2011].

[24]William de la Mare targeted Aquinas affirmation of unicity in Correctorium Fratris Thomae in 1279.

[25][Suárez, Disputationes metaphysicae, 15.1.7] as quoted in [Pasnau, 2011]]. The text is somewhat ambiguous: Suárez goes on to claim that the whole variety of accidents and powers has its root and unity in the form.

[26]From C. Adam and P. Tannery eds., *Oeuvres de Descartes*, rev. ed., 12 vols., (Paris: Vrin/CNRS, 1964-76), as quotes and translated in [Pasnau, 2011].

[27]See Rene Descartes to Morin, 12 September 1638, in The Philosophical Writings of Descartes, vol. 3, ed. J. Cottingham et. al. (Cambridge: Cambridge University Press).

[28]See R. Boyle, The Origin of Forms and Qualities, in The Works of Robert Boyle, ed. m. Hunter and E. Davis (London: Pickering & Chatto, 1999-2000).

[29]H. Oldenburg, Correspondence, ed. and trans., A.R. Hall and M.B. Hall (Madison: University of Wisconsin Press, 1965), III:67.

[30]See Works of Boyle, V:305.

[31]See P.-S. Marquie de Laplace, A philosophical essay on probabilities, trans. F. W. Truscott and F.L. Emory (New York: John Wiley & Sons, 1902).

[32]Sophisticated forms of Cartesian dualism are experiencing a revival of interest in some quarters, however, among philosophers frustrated by the problems with physicalism. For an overview, see [Loose et al., 2018].

[33]For Aquinas, the soul was conceived as the form of the body. For a contemporary exposition of his view, see [Leftow, 2001].

Chapter 2

# Science and the new Aristotelianism

> *Physicists and chemists presuppose that change is possible and then go on to talk about the specific nature of specific changes... Although science is not itself metaphysics, metaphysics of science is unavoidable.*
>
> – Tim Crane, *Aristotle Returns*[1]

## §2.1. Against naïve scientism

In this thesis, I shall be considering some challenges posed to micro-monist conceptions of nature by the phenomenon of quantum entanglement in microscopic systems (in Part II), and the emergence of thermochemical phenomena in macroscopic systems (in Part III). The purpose of this chapter is to lay out the metaphysical tools with which I hope to tackle my problems and construct new metaphysical models.

Metaphysics is concerned with supplying a general account of the structure of reality and an inventory of what fundamentally exists. Yet one might ask: what is the point of metaphysics for modern philosophers, who can claim (unlike Aristotle) to be informed by empirically successful theories like quantum physics? Why not simply repeat (or claim to accept) whatever our 'best sciences' happen to say about reality, and focus one's attention upon the logic and grammar of the language in which scientists happen to say it? I suggest there are at least four reasons why adopting a naïve form of scientism, in which our best scientific theories are presumed to be self-sufficient for describing reality, will fail to produce a satisfactory account of nature that accommodates the possibility of scientific inquiry.

First, it is not clear *what* a physical theory, like quantum mechanics, is in fact asserting about the world, solely on the basis of its own formalism. For example, the physical meaning of the superposition principle, which permits quantum states associated with mutually exclusive measurement outcomes to be simultaneously combined, is only settled by adopting an *interpretation* in which the scope of its application is fixed. (I discuss the 'measurement problem' that arises in quantum mechanics in Chapter 3.) It would be a naïve sort of realist who claimed to be able to read off the ontology of nature from the formalism of quantum mechanics without offering an account of how determinate measurement outcomes are obtained in experiments. The problem with naïve scientism is that there are a number of *empirically equivalent* interpretations of quantum mechanics, for all practical purposes, so we must find other rational grounds for adjudicating between them.[2]

Secondly, in attempting to articulate what some physical theory says about the world, like quantum mechanics, physicists invariably deploy *background concepts* that the theory itself presupposes yet does not explain. Such concepts may not be metaphysically innocent. For example, quantum mechanics presupposes that the quantal properties of a physical system have the potential to change in accordance with the Schrödinger equation, but it does not provide an account of change, nor explain whether this law governs the way systems evolve *necessarily* or only *contingently*. (I consider metaphysical accounts of how properties change in Chapters 4–6.) It would be a pompous sort of eliminativist who claimed to disbelieve in the reality of change because it is inexplicable in terms of some physical theory, since it would be difficult to make sense of our ability to perform experiments without invoking the concept of change. The trouble with naïve scientism is that it forestalls the possibility of offering intelligible interpretations of physics.

Thirdly, scientists are interested in measuring a variety of phenomena that emerge at different physical scales, yet we have good reason for considering the space of physical possibilities for macroscopic systems, defined by quantum statistical mechanics, to be irreducible to the space of possibilities for microscopic systems, defined by standard quantum mechanics.[3] Hence we have reason to doubt whether the values of every property emerging at higher-scales is reducible to the values of microphysical properties. (I discuss issues of theory reducibility in Chapter 7.) For example, in addition to detecting particles, scientists also conduct experiments to measure properties like temperature. It would be a crass reductionist who supposed the truth about the temperature of liquid to be determined by a simple averaging of the properties of its microscopic particles, such as their 'mean kinetic energy' (a false claim, but often repeated by philosophers).[4] Another difficulty with naïve scientism is that there is no single scientific model in which all of these properties can be defined simultaneously.

Fourthly, since the possibility of scientific inquiry depends on the existence of scientists who conduct observations and perform experiments, we require a principled account of how the 'scientific' and the 'manifest' image are supposed to be related (to adopt Wilfred Sellars' terminology). For example, a scientist who detects the position of a microscopic particle *perceives* a change in the pointers on a macroscopic instrument, and consequently *believes* the particle to be in one place rather than another. Yet it would demonstrate an absurd lack of self-knowledge to advance an account of reality on the basis of quantum mechanics in which psychological states cannot be accommodated, either because they had been simplistically eliminated or because the account undermines any conception of how their contents could be determined. (I discuss the problem of recovering the manifest image in a quantum world in Chapter 8.) The problem with naïve scientism is that one may end up excluding scientists from the world they investigate.

## §2.2. Against radical scepticism

Given the underdetermination of ontology by science, there can be no question of our avoiding the metaphysics of science if we are to understand what scientific knowledge is suppose to be knowledge *of*. Some philosophers, however, have doubted whether there *are* any facts about nature which are eligible for realist interpretation. After all, human beings find themselves caught up within a multitude of epistemic practices in which they *impose* order upon nature, according to whatever their aims and interests happen to be, rather than simply *discover* such orderings ready-made. Nonetheless, it is reasonable to ask whether, having taken into account our mutable conventions, and granted optimal epistemic conditions, it is possible in principle to state *something* about the world that could either be true or false, independently of our preferences and practices. Such propositions would depend for their truth-values upon an ordering that is *intrinsic* to nature, rather than one we impose on it.

To answer this question in the negative would be to deny, along with Immanuel Kant, the possibility of our picking out features of an objective order (or, in Kantian parlance, the properties of *things-in-themselves*). Such a world has been described as one in which 'reference slides freely across the surface of noumenal waters' [Smart, 1995, p.309], whilst those who adopt such a stance might be compared to the Venetian judge in *Le Sicle de Louis XIV*, who, when asked for his impressions of the gardens of Versailles, confessed that he was most struck by seeing himself there.

Yet a thoroughgoing Kantian scepticism about reference is difficult to maintain. As Tim Button complains, how is one even supposed to *formulate* the worry that our terms of reference express *nothing* about the world itself? More specifically, how is one supposed to entertain the sceptical suggestion that "the word 'cats' does not *refer* to cats", for example, since in order to do so, one would have to be able to think *about* cats in order to contemplate the suggestion that the word 'cat' fails to pick them out. Nor is it sufficient merely to *articulate* the sceptical claim, "the word 'cats' does not refer to cats"; if this sceptical scenario were the case, then the last word of this sentence would fail to pick out any cats [Button, 2013, pp. 59-60].

Of course, there are more qualified 'Kantian' positions one might adopt that require some metaphysical commitment: one might accept the objective existence of objects and properties, for instance, whilst confessing irremediable ignorance regarding their identities [Langton, 2001, Stratmann, 2018]. Nonetheless, to acknowledge the possibility of our stating *something* about the world that may either be true or false, independently of our preferences and practices, is to affirm the possibility of engaging in metaphysics, and hence of giving some account of what it is that we are referring to whenever we make propositional claims about things like cats.

## §2.3. Metaphysical grounding

### i. *Grounding and realism*

Metaphysics would be vacuous, however, if it did nothing more than affirm the truth of everything that 'common sense' has to say about the world, prior to engaging in philosophical reflection. A metaphysician, in that case, would be like some benevolent but senile academic at a college dinner who is just happy to see everybody enjoying themselves. Kit Fine identifies two ways in which metaphysics has sought to add value to scientifically informed discourse about reality, which I shall designate as the *sceptical Quinean* approach, and the *critical Aristotelian* approach [Fine, 2001].[5] Both kinds of philosophers style themselves as being part of a realist tradition of scientific inquiry, which is directed toward uncovering the truth about nature.

According to sceptical Quineans, the task of metaphysics is to specify those things that *really* exist, as opposed to those things that are more commonly *believed* to exist. In donning this mantle, philosophers seek to distinguish themselves by adopting a superior epistemological stance that is informed by the natural sciences. Following Quine's famous paper, "On what there is", the sceptical Quinean considers the task of metaphysics as proceeding by extracting *existence claims* from our best scientific theories, by translating them into first-order logic, determining what their bound variables have to range over in order for their results to be true, and adopting the elements from these domains as basic posits in a primitive ontology [Quine, 1948]; a recipe neatly summarised by Quine's famous dictum, 'to be is to be the value of a variable'. Quine thus endorses a *univocal* notion of being. Insofar as we accept the scientific theory in question, these are the only entities to which we are ontologically committed. The rest is ideology. The fundamental question of metaphysics, then, is to determine *what there is*.

Alternatively, according to the critical Aristotelian approach, the purpose of metaphysical analysis is not to tame the rampant tendencies of other people to make false existential claims (of course there are particles and people and sets!), but rather to organise our beliefs about what there is to reflect an *ordering* within nature that exists between that which is fundamental and that which is derivative. As Sider observes: "One doesn't get far in metaphysics without some sort of distinction between fundamental and nonfundamental facts, or between more and less fundamental facts." Once this distinction has been admitted, however, "one will want to say that nonfundamental, or less fundamental, facts 'rest' in some way on fundamental, or more fundamental, facts" [Sider, 2018].

Following Schaffer's paper, "On what grounds what" (named in contrast with Quine's), the critical Aristotelian conceives the task of metaphysics as being to 'limn this structure', identifying those entities comprising the *sparse structure of being*, and the grounding relations that generate the abundant superstructure of derivative entities [Schaffer, 2009]. This sparse structure consists only of those things that God would have to create in order to generate the whole abundant superstructure of being. Schaffer attributes this approach to Aristotle, for whom categorical distinctions arise from the many *equivocal* senses of 'being', which derive in turn from a single focal sense of being as attributed to *substances*.

Schaffer contrasts the sceptical Quinean and the critical Aristotelian programmes in terms of their different conceptions of the target that is to be explained. For the Quinean, nature is *flat*, and the task of metaphysics is, so to speak, to "solve for $E =$ the set of entities". In this metaphysical scheme, an entity is either to be found within this set, or it is simply non-existent, and the set $E$ is without any additional structure. For the critical Aristotelian, by contrast, nature is *hierarchical*, and the task is to "solve for the pair $\langle F, G \rangle$", where $F$ are the fundamental entities and $G$ are the grounding relations. In this metaphysical scheme, there are four possibilities: an entity is either in $F$, or in $G$, or it is generated from $F$ via $G$ (in which case, it may be found nested within further levels of structure), or it is non-existent. Metaphysical categories are merely ways in which things depend on the substances in $F$. In other words, they are nodal points within a structure of being, having no separate being of their own, over and above the substances upon which they depend. The fundamental question of metaphysics, then, is to determine *what grounds what*.

There is good reason to favour the critical Aristotelian approach to metaphysics over the sceptical Quinean approach, inasmuch as the latter appears to be 'parasitic' upon the former. This is reflected, for instance, in Quine's privileging of *physics* as providing the best theory for the analysis. Why do so? "The answer is not that everything worth saying can be translated into the technical vocabulary of physics; not even that all good science can be translated into that vocabulary," according to Quine. "The answer is rather this: nothing happens in the world, not the flutter of an eyelid, not the flicker of a thought, without some redistribution of microphysical states" (1981: 98). How does Quine know this? In a world in which there is metaphysical grounding, as Schaffer observes, it makes sense to fix the direction of analysis 'groundwards', and to keep faith in seeking out what those fundamental grounds might plausibly be, whilst it is unclear why a Quinean should not regard other forms of human inquiry as equally inquiries into what exists, and hence favour a more profligate ontological relativism.[6]

The parasitic nature of the Quinean approach to realism, which influenced the metaphysics of David Lewis [Janssen-Lauret, 2017], is also reflected in Lewis's notion of *sparse natural properties*, upon which all the other properties of nature are said to supervene and upon which the whole truth about the world is supposed to depend. According to Lewis, the 'sharing of [sparse properties] makes for qualitative similarity, [sparse properties] carve at the joints, they are intrinsic, they are highly specific, the sets of their instances are *ipso facto* not entirely miscellaneous, and there are only just enough of them to characterize things completely and without redundancy' [Lewis, 1986, p. 60]. The restriction of priority relations in this way is intelligible in a world in which there is metaphysical grounding [Schaffer, 2004], whereas for Lewis it must be caste (implausibly) as a carefully calculated tradeoff between ideology and explanatory power (what is the exchange rate?).

The concept of metaphysical grounding also provides us with a straightforward way of escaping eliminativist claims, such as van Inwagen's assertion that, since tables and chairs are not part of the basic furniture of the world (and since they do not compose a 'life') they cannot actually exist [van Inwagen, 1995]. According to Schaffer and Fine, our ontological commitments are not limited solely to the domain of fundamental physical entities, whatever those might happen to be, but extend to the derivative domain of abundant entities, which they happen to ground.

Finally, the *problem of the singleton* in contemporary metaphysics offers a powerful reason for admitting the existence of metaphysical grounding, which has been acknowledged by van Inwagen as a problem for committed Quineans [van Inwagen, 2019]. For instance, it is clear that the set $\{Socrates\}$ and the person Socrates exist in all of the same possible worlds, yet it seems evident that the existence of $\{Socrates\}$ depends upon the existence of Socrates, and *not* vice versa. In that case, granting the existence of such mathematical objects as sets, we have good reason to take the grounding of the existence of one object in the existence of a more fundamental object to be a real feature of the world, and hence to prefer critical Aristotelianism over sceptical Quineanism.

### ii. *Grounding and explanation*

The concept of *metaphysical grounding*, although arguably enjoying a long history in Western philosophy [Correia and Schnieder, 2012], was only recently formally introduced into the analytic tradition by Fine in 2001, has been further developed in notable works by Schaffer and Gideon Rosen (see [Schaffer 2009] and [Rosen, 2010]), and is receiving increasing attention among contemporary metaphysicians.[7]

The concept of grounding is at work in claims in which one thing is said to obtain *in virtue* of another. For example, the fact that a proton is massive and electrically charged is *in virtue of* the fact that it has mass and the fact that it is has electric charge. Or again, the fact that an electron is accelerating in a Stern-Gerlach device obtains in *virtue of* the fact that it is being acted upon by the Lorentz force produced by a magnetic field. We are apprised of numerous intuitions concerning what grounds what, whilst different systems of grounds can be put forward and appraised on the basis of their simplicity, breadth, coherence, or non-circularity [Fine, 2001, p.22].

The concept of grounding, however, must be teased apart from other concepts that purport to do similar jobs. When one thing holds in virtue of another, there is supposed to be some *modal connection* between them: necessarily, if an electron is acted upon by a net Lorentz force, the electron will experience a net acceleration. Nonetheless, modal connections may obtain between two sets of facts without one happening *in virtue of* the other. (Fine offers an arresting counterexample: *necessarily*, if it is snowing, then $2+2=4$.)[8] In order to play a fundamental explanatory role, however, grounding must somehow close the gap between *explanans* and *explanandum*. It may be seen to do so if, when $x$ is said to ground $y$, it is because $x$ *determines* $y$ to be the case, in some appropriate sense.

However, the notion of *causal determination* is not sufficient to capture the concept of metaphysical grounding, since one thing might be causally determined by another thing, yet still have some reality over and above that which determines it. For example, the flow of an electric current may cause an electromagnet to have the power to attract iron filings, but the electromagnet does not depend for its reality upon this flow of electric current. In other words, causal determination allows for the possibility of an *ontological* gap between them.

Likewise, the concept of *supervenience* does not capture the concept of grounding, because supervenience, unlike grounding, is *not* necessarily an asymmetric relation. Lewis believed that properties should be sorted into 'sparse' and 'abundant' collections, where abundant properties, like mental properties, are supposed to supervene upon sparse properties, like the properties invoked in the ideology of our 'best physics'. However, if the mental merely supervenes on the physical it might still be the case that the physical is best understood in terms of the mental. In other words, the notion of supervenience, though it may have its uses, can offer no assurance that the 'reduction' should go one way rather than the other. Echoes of the concept of metaphysical grounding can also be found in the intuition that moral features depend upon natural properties, for instance, and the intuition that truth is grounded in being, rather than the other way round.

The concept of grounding is also to be distinguished from the broader concept of *ontological dependence*, inasmuch as metaphysical grounding may be considered a species of ontological dependence without being the only species within this genus. For example, every organism may be considered to be ontologically dependent upon the *prior* existence of the parent organisms which conceived it at time $t'$, but it does not follow that an organism's existence, at the present moment $t$, is grounded by the parents' existence at time $t' < t$. According to Koons, grounding and ontological dependence are to be distinguished according to their *direction* of dependency. Metaphysical grounding is a necessitating relation: when some fact $F$ wholly grounds some other fact $G$, it is impossible for $F$ to exist without $G$'s existing. This is not the case regarding the dependency relation that holds between parent and child. If some object $O$ is ontologically dependent upon some other object $P$, then it is impossible for $O$ to exist without $P$'s existence. Whilst the mother can exist apart from the child, the child depends on the mother's having existed at some point.

In its logical form, grounding is similar both to causation and parthood, in that the relation of grounding, conceived as a two-place predicate $xGy$, is irreflexive, transitive and asymmetric. The relation $G$ thus induces a partial ordering over the great chain of being, yet differs from either causation or parthood in requiring the existence of a set of minimal elements (or single element) at the roots of this structure. More precisely, we may say that $x$ is fundamental if and only if nothing grounds $x$, and that $x$ is derivative if and only if there is something that grounds $x$.

Grounding, then, is to be conceived as a fundamental form of explanation – a *metaphysical explanation*, rather than a causal explanation – which cannot be analysed in terms of Humean supervenience or causal determination. As Fine puts it, 'ground... stands to philosophy as cause stands to science' [Fine, 2012, p.40]. A critical Aristotelian realism that embraces metaphysical grounding should thus be distinguished from the neo-Humean and Armstrongian programmes that dominated analytic philosophy in the last century. As Koslicki observes, the introduction of grounding within the analytic tradition constitutes a reorientation of contemporary metaphysics toward the classical and medieval philosophical tradition, as well as a broadening of its domain of discourse, inasmuch as both ancient philosophers like Aristotle and 'continental' philosophers like Husserl have recognised the importance of questions of ontological dependence in metaphysics [Koslicki, 2012].

### iii. *Grounding and objects*

The concept of grounding offers alternative ways of distinguishing between different metaphysical positions held by philosophers concerning the objects of scientific inquiry. For example, in the philosophy of time, it has been suggested that the difference between presentists and four-dimensionalists is captured by the diagonistic of whether or not they subscribe to the existence of temporal parts, on the assumption that, since presentists believe that only the present moment exists, they must therefore deny that any thing that exists has temporal parts. However, as Schaffer points out, the distinction can be framed more intuitively by the question of whether an object that persists is *grounded* in its temporal parts, or whether the object *grounds* its temporal parts. The presentist, on this view, is not committed to denying the existence of temporal parts, but rather to affirming the existence of objects which are more *fundamental* than any of their temporal parts.

Here is another example that is of relevance to debates about realism and anti-realism in the philosophy of science: one might explain Kant's approach to saving human freedom from physical determinism as one in which the physical world of

Newtonian mechanics describes a phenomenal realm that is ultimately *grounded* in the noumenal realm of freedom, rather than the phenomenal world being grounded in the physical world (see [Stratmann, 2018] and [Koons, 2018a, p.390]). In that case, facts about the Newtonian physical world will (partly) depend upon facts about the phenomenal world, rather than (simply) upon facts about physical things in themselves. Similarly, for neo-Kantian philosophers of science, like Hasok Chang, facts about the properties of objects in the physical world might also be considered to depend upon facts about the preferences and practices of human subjects in the noumenal world. Scientific inquiry, in that case, is an inquiry into what is *real*, since what is real encompasses what is grounded, but it is not an inquiry into what is *fundamental*, since physical facts depend upon facts about human subjects.

For the critical Aristotelian, by contrast, the physical world contains fundamental objects with properties that exist independently of our preferences and practices, as well as objects and artifacts that are derivative, and scientific inquiry *is* concerned with disclosing their true natures. Since the categories of being fundamental and of being derivative are both exhaustive and exclusive, it follows that $x$ is an existent if and only if $x$ is fundamental *or* $x$ is derivative. However, the partial ordering induced by the relation of grounding gives rise to a richer variety of objects than are acknowledged among sceptical Quineans, enabling the following mereological distinctions suggested by Schaffer:

*Integrated whole*
GR/I: $x$ is an *integrated whole* if and only if $x$ grounds each of its proper parts.

*Aggregate*
GR/II: $x$ is an *aggregate* entity if and only if each of $x$'s proper parts together jointly ground $x$.

*Interdependent entities*
GR/III: $x$ and $y$ are *interdependent* entities if and only there is an integrated whole of which $x$ and $y$ are proper parts.

For example, tables and chairs may be considered aggregate entities, subject to the existence of suitable grounding relations, since they are composed of a collection of more fundamental parts. Contra van Inwagen, who embraces a Quinean metaontology, we need not eliminate them from our ontologies. However, it is possible for an entity to be fundamental and also to have derivative parts. According to Schaffer, the cosmos itself is an integrated whole that grounds all of its parts [Schaffer, 2010]. I shall return to this controversial claim and will consider examples of interdependent entities in the following chapter.

iv. *Criteria for fundamentality*

Schaffer suggests three criteria for fundamental objects in nature that are subject to scientific inquiry, which – following Aristotle – he refers to as *substances* [Schaffer, 2009, pp.377-78]:

*Minimal Completeness*
FS/I: A set $S$ of substances at world $w$ is *complete* for $w$ iff $S$ serves to characterise $w$, by providing a supervenience base for $w$, and $S$ is *minimally complete* for $w$ iff (i) $S$ is complete for $w$, and (ii) no proper subset of $S$ is complete for $w$.

*Metaphysical Generality*
FS/II: The ways the substances could be just are the ways the world could be: the substances have a form that fits all metaphysical possibilities.

*Empirical specifiability*
FS/III: A substance has an intrinsic, empirically specifiable content that is informed by fundamental physics.

I shall consider the *intrinsic properties* of such a substance to be wholly grounded in its fundamental monadic properties, and regard a substance $S$ to have a physical property $P$ intrinsically just in case $S$ has $P$ and every possible duplicate of $S$ also has $P$. In what follows, however, I shall part ways with Schaffer in describing the *nature* of a substance's intrinsic properties and their relation to scientific inquiry.

## §2.4. Causal powers

i. *Powers and realism*

According to scientific realists, scientific inquiry is our best way of finding out the properties of nature. Recent work in the metaphysics of science has been marked by a resurgent interest in the relationship between the properties that exist in nature and the causal powers they confer upon physical entities. Contemporary metaphysicians can be divided into *powerists* and *Humeans* according to whether they consider these powers to be conferred contingently or necessarily.

According to neo-Humeans, like Lewis, the relationship between properties and their powers is entirely contingent, since none of the regularities of nature are necessary. Likewise, Quine, who influenced Lewis in his espousal of Humeanism [Janssen-Lauret, 2017], opposed the existence of any non-contingent modalities in nature, connecting the distinction between necessary and contingent attributes with Aristotle's distinction between *essence* and *accident*, which he dismissed as indefensible [Quine, 1960, pp.198-99].

The Humean assumption of contingency, however, whilst reflecting the natural philosophy of early scientists, like Francis Bacon,[9] and the antipathy toward Aristotle that can be found in the writings of Galileo Galilei, for instance, is not metaphysically innocent. Suppose we ask the question: what makes a property the property that it is? The Humean view has the counterintuitive consequence that, since *any* nomic profile is supposedly compatible with the identity of a given property, there is a possible world in which something has exactly the same properties but the powers have been *swapped*: two negatively charged particles might attract one another, rather than repel, whilst two oppositely charged particles might repel instead of attract [Bird, 2007, pp.70-81]. The fundamental properties of nature, on this view, are *categorical* properties, which can be described without reference to any happenings or conditions. In other words, a Humean world 'condemns us to necessary ignorance' concerning the *identities* of physical properties [p.78].[10]

For powerists, by contrast, the causal powers that are conferred by a fundamental property are intrinsic to the nature of that property itself. Such properties are properly described in terms of what happens under certain conditions, as it is not possible that the powers of two fundamental properties might ever be swapped. The essence of a property, in that case, might be specified by a 'cause-function', which maps 'from the circumstances and potential causes to the property in question', and an 'effect-function', which maps 'from the property in question and circumstances to potential effects' [Schaffer, 2005, p.2]. The powerist assumption of necessity has the anti-Humean consequence that some laws of nature are necessary rather than contingent. If a system is situated in the appropriate circumstances, its causal powers will manifest their nomic profiles. So, should we be powerists or Humeans?

Humean philosophers, on the one hand, have attempted to avoid ontological commitment to the existence of powers by offering various ways to analyse of power ascriptions.[11] A notable attempt is Gilbert Ryle's *conditional analysis*, in which something's power $\phi$ to give a response $R$ to a stimulus $S$ is predicated on the truth of the counterfactual, "it would give a response $R$ if it were the case that $S$" [Ryle, 1949]. For example, we might consider a locked door to have the power to resist being opened, just in case it would fail to open if it were pushed.

The conditional analysis, though widely adopted, suffers from a number of problems, such as 'finking' and 'masking' counterexamples. A finking counterexample exploits the fact that the conditions for an object's acquiring or losing a disposition might be the same as the disposition's stimulus conditions [Martin, 1994]. For example, a locked door that has the power to resist being opened might open automatically when it is pushed, if its locking mechanism has been rigged to a suitable circuit that unlocks the door whenever it is touched. A masking counterexample exploits factors that prevent or block the manifestation of a power, even though it seems we should predicate the property nonetheless [Johnston, 1992, Bird, 1998]. For instance, a poisonous substance surely remains poisonous, even if an antidote is ingested, but on the conditional analysis it fails to count as such.

A subsequent generation of empiricists adopted a more sophisticated approach. Recognising that one of the chief defects of the conditional analysis lay in its failure to associate dispositions with objective properties, *causal analyses* were suggested in which something has the power $\phi$ to give response $R$ to a stimulus $S$ just in case it has some categorical property $P$ that would *cause* it to give response $R$ if it were to undergo stimulus $S$. For example, we may say that sugar has the 'power' to dissolve in water, within a certain temperature range, because it has a certain molecular structure, and having this structure 'causes' it to dissolve when placed in water (which is to say, if we are Humean, there is an observed regularity of things having such a structure dissolving when they are placed in water).

As critics have pointed out, however, this amendment fails to avert finking and masking counterexamples, and introduces the additional problem of 'deviant causal chains' [Mayr, 2011, pp.175-80]. A deviant causal chain can bring about the characteristic response $R$ of a disposition $\phi$ to a stimulus $S$, without being a manifestation of $\phi$ [Smith, 1977]. For example, an army of submerged nanobots that have been programmed to pull apart any molecules of sucrose do not manifest the power of sugar to dissolve in water. It seems, then, that the exercise of a power requires the right sort of process, not simply a causal chain between its characteristic stimulus and response. In short, it does not appear that powers can straightforwardly be displaced from scientific explanation by analysis.

Powerist philosophers, on the other hand, have sought to press their advantage by compelling an ontological commitment to powers as a consequence of 'taking scientific practices seriously'. Brian Ellis and Nancy Cartwright, for instance, have argued that we should be realists about powers because ascriptions of powers are indispensible to scientific explanations. According to Ellis, powers are necessary to prevent an ontological regress, since 'there never seems to be any point at which causal powers can just drop out of the account' [Ellis, 2014, p.76]. Similarly, Cartwright claims that certain composite phenomena can only be explained in terms of the *exercise* of powers whose manifestations are not realised [Cartwright, 2017], as in the case of a charged particle suspended motionless between two similarly charged electric plates.

Yet neither of these claims seems entirely compelling. As Chakravartty observes, it is one thing to argue that there are explanatory contexts in which dispositional ascriptions are indispensable; that is to say, one might argue for the *linguistic acceptance* of dispositional predicates in scientific explanations. It is another thing to suppose that such arguments compel an *ontological commitment* to the existence of powers as occurrent properties in nature. After all, it seems a determined Humean could take powerful descriptions as being elliptical for categorical descriptions, whether or not they can in practice offer a relevant categorical description. Moreover, Cartwright appears to be begging the question against Humeans, since the explanatory context in which powerists might appeal to the possibility of powers *exercising* without *manifesting* does not arise for Humeans.

Powerist philosophers have also sought to compel ontological commitments by appealing to the efficacy of abstraction in scientific practice, and using powers to explain it. Roy Bhaskar and Andreas Hüttemann, for instance, have argued that the existence of powers explains why certain regularities that hold in the isolated conditions of the laboratory also hold outside of these artificial conditions. According to Bhaskar, it is because scientists successfully isolate powers, by abstracting away from the world, that the knowledge they generate in specific contexts is exportable to wider contexts [Bhaskar, 1978]. According to Hüttemann, it is impossible to explain how laws, conceived in abstraction, are applicable to concrete physical conditions, without assuming they refer to powers [Hüttemann, 1998].

Yet such arguments, although suggestive, are unlikely to trouble Humeans. As Chakravartty observes, the possibility of exporting specific laws discovered in abstraction and successfully applying them within another context depends on whether the conditions in both contexts are sufficiently similar, since causal powers typically only manifest in certain conditions. Whether one regards the term 'solubility' as picking out a concrete power of the sugar, for instance, or referring to an abstract molecular structure, the question of whether the external conditions are sufficiently similar for those particular laws to apply remains the same. There is nothing about a powers ontology *per se* that guarantees the general applicability of specific laws.

It seems, then, that the answer to the question of whether we should be powerists or Humeans is not one that can be settled simply by appealing to scientific practices, and that the distinction between dispositional and categorical properties that scientific explanations demand has no logical implications for the existence of powers as genuinely occurrent properties within nature. Nonetheless, an ontological commitment to powers might be motivated by considering what concept of properties is in keeping with the *nature of scientific inquiry*, insofar as scientific inquiry is conceived as our best approach to finding out the *truth* about nature. According to Chakravartty, powerism 'represents an ontological commitment that is maximally consistent with a view of the sciences according to which they are our best hopes for learning whatever contingent truths about the natural world as may be within our grasp' [Chakravartty, 2017]. To put it another way, I suggest that an ontological commitment to powers is 'fitting' for scientific realists who locate themselves within the *Aristotelian empirical tradition* (see Chapter 1), which is characterised by a certain confidence in the power of human reason to uncover truths about nature. Conversely, 'scientific' realists who disavow powers in favour of categorical properties are guilty of a kind of 'pragmatic incoherence', since they must claim that the natures and identities of the properties investigated by the sciences are not empirically specifiable, but have hidden quiddities. As I shall argue in later chapters, a Humean approach to ontology, which excludes the existence of fundamental powers, leads to difficulties in affirming the *truth* about nature's laws (see Chapters 4 & 5).

ii. *Powers and explanation*

The concept of causal powers was introduced within mainstream analytic philosophy by Rom Harré and E. H. Madden in 1973 [Harré and Madden, 1973]. It was further developed by George Molnar in the 1990s [Molnar, 2006], and has recently become the foundation of a non-Humean theory of causation put forward by Stephen Mumford and Rani Lill Anjum [Mumford and Anjum, 2011]. It was introduced into contemporary philosophy of science by Nancy Cartwright, under the guise of 'causal capacities' [Cartwright, 1994, Cartwright, 1999]. Anna Marmodoro has expounded its Aristotelian roots by linking the concept to Aristotle's discussion of potentiality and actuality [Marmodoro, 2014, chp. 1].

A world with powers is a world in which objects in nature have fundamental *agency*, since causal powers are features of reality that bring about change, and they are irreducible to categorical properties, which make no reference to change.[12] More precisely, causal powers are generally understood to bring about change by *conditional necessity*, such that, when a power is situated in the appropriate circumstances, it will bring about its manifestation necessarily.[13] A power is typically individuated by reference to some characteristic manifestation, but exists independently of whether or not it is exercised. The power of water to dissolve sugar, for example, is retained whether or not it is exercised by adding sugar to tea.

The existence of causal powers in nature, according to some powerists, divides the world into agents and patients connected by causal processes, in which cause and effect are united within a single whole [Koons and Pickavance, 2017, chp. 6 & 28]. (For John Heil, by contrast, 'the model here is not a chain, but a net, or perhaps two playing cards supporting one another upright' [Heil, 2005].) When an object exercises a causal power to bring about some change, it initiates a causal process, beginning with the agent's *active power*, which encompasses the process of change that takes place in the patient, whilst the patient exercises a corresponding *passive power*. The agent's power to bring about change, and the patient's power to suffer change, exist within relations of ontological dependence [Marmodoro, 2013b], since causal powers are defined by *what* they change, as well as the type of change that they bring about, and active powers depend upon passive powers for their manifestation.

Metaphysics and the philosophy of science overlap on the topic of the laws of nature, inasmuch as metaphysicans of science wish to know whether there is something in the world that explains the phenomenal regularities we associate with laws, whilst contemporary philosophers of science have noted that many law statements in the sciences do not appear to describe universal regularities, but regularities that are in some sense context-dependent, depending on certain physical conditions. According to powerists, causal powers explanatorily ground the law-like regularities that scientists discover in their experiments, since causal powers are associated with nomic profiles, and context-dependence is built into the very definition of powers in terms of the conditions of their manifestation. In other words, laws may be understood as expressing the essence of powers [Bird, 2007, chp. 9].

Humeans, on the other hand, neither want nor need an explanation of law-like regularities: the order of explanation goes in the opposite direction. According to standard Humean accounts, it is a contingent fact that most instances of sugar being wet are followed by instances of sugar being dissolved, whilst universal laws of nature are supposed to account for particular 'dispositions'. As Humeans point out, it would be fallacious to *infer* the existence of non-contingent relations in nature from the existence of conceptually linked modes of description. Causal powers are merely the projection onto reality of a certain mode of description in scientific practices.[14]

Yet we should not conceive the adoption of powerism as simply a matter of adding modal glue to a Humean mosaic of properties, depending on whether or not we find Humean explanations satisfactory. Rather, the justification for the powerist's adoption of powers lies in adopting a coherent alternative to Humeanism that is maximally consistent with a conception of scientific inquiry in which the sciences are concerned with uncovering truths about nature. In Chapter 4, I will discuss conceptual problems that arise in a recent attempt to form a Humean supervenience base for the laws of quantum mechanics, when those laws are taken to be *true* laws.

### iii. *Powers and objects*

Nonetheless, modern philosophers have often expressed suspicions about explanations that appeal to the powers of objects in nature, frequently citing the French playwright Moliére in *Le Malade imaginaire*, in which a physician famously responds to the question of why opium causes drowsiness by observing that it has *virtus domitiva* (that is, a power to cause drowsiness). Whilst the response of the physician is vacuous, the Humean moral that has frequently been drawn is mistaken: as Chakravartty points out, what we learn from this example concerns the contexts of explanations, rather than the existence of powers [Chakravartty, 2007, pp. 125-6].

Chakravartty suggests a different example, in which a patient asks why they feel drowsy after completing their morning routine, and the physician responds that it is because the opium they took at midday induces drowsiness. In this case, the explanation *is* informative, locating the cause of the condition within a particular substance ingested at a specific time, rather than, say, a gas spread throughout the world which the patient has been breathing all morning. It is also an empirical claim, which may turn out to be mistaken, following further scientific investigation.

Let us consider the structure of the physician's claim a little more carefully. To say that opium has a power to cause drowsiness is to predicate a property $\phi$ of a substance $S$, in virtue of which $S$ produces a manifestation $M$ in the right circumstances. This is an informative claim, since the power $\phi$ of $S$ to bring about

$M$ might not be intrinsic to $S$, but due to some feature of its physical environment. Since Humeans regard the relationship between physical properties and the powers they confer to be entirely contingent, however, no causal power could be intrinsic to any object in nature; rather, the causal powers of any object depends upon the laws of nature, which in turn depend upon nothing less than the entire pattern of physical properties distributed throughout space and time.

A diagnostic for pulling apart powerist and Humean attitudes towards powers, then, can be found in the question of whether some causal powers in nature are *intrinsic* to the objects that have them, or whether the powers of all objects in nature only depend *extrinsically* upon how they are situated within their environments. The reason the physician's claim in *Le Malade imaginaire* is vacuous is because the *content* of his answer is contained within the *context* of the patient's question: we already know that opium has the power to induce drowsiness. We might usefully rephrase the question, however, by asking whether this is a *fundamental* power.

iv. *Criteria for powers*

In the light of this discussion concerning the relation of powers to scientific inquiry, and inspired by Molnar [Molnar, 2006], I suggest three criteria that causal powers should meet if they are to play an explanatory role in an ontology of nature:

> *Intrinsicality of powers*
> CP/I: Something is *essentially* powerful because it possesses an *intrinsic* power, not (simply) because of its physical environment.
>
> *Objectivity of powers*
> CP/II: Powers are real, occurent properties in nature: they are not reducible to properties that can be described without reference to happenings or conditions.
>
> *Empirical specifiability of powers*
> CP/III: The causal powers of an object have nomic profiles that are empirically specifiable by the physical sciences: they are not hidden quiddities.

## §2.5. A neo-Aristotelian image of nature

I have discussed the rise of a critical Aristotelian approach to metaphysics, which is opposed to the sceptical Quinean approach that dominated analytic philosophy in the last century. I have also noted a growing sympathy among contemporary philosophers for the Aristotelian notion of powers, in defiance of the long-standing Humean embargo of necessary connections. However, not every philosopher who embraces the notion of grounding admits the existence of powers (for instance, see [Schaffer, 2005]), nor does every philosopher who adopts an ontology of powers accept the presence of hierarchical structure (for example, see [Heil, 2016]). In the course of this thesis, I mean to motivate and contribute toward a *neo-Aristotelian* metaphysics of science that combines a critical Aristotelian approach to metaphysics with a scientifically informed commitment to an ontology of powers.

### i. *Criteria for neo-Aristotelian models*

I shall regard a contemporary metaphysical model to be 'neo-Aristotelian' if it conforms to the following criteria [Simpson et al., 2017, pp.1-3]:

*A hierarchical structure*
NA/I: Nature admits a hierarchical structure, in which some objects are fundamental and other objects are derivative.

For neo-Aristotelians, being is not a univocal notion. As Aristotle observes, 'there are many senses in which a thing may be said to "be"' [Aristotle, Metaphysics IV.2]). An 'equivocal' conception of being may be introduced within a contemporary metaphysical model by adopting the notion of *grounding* (see Section 2.3), which requires some entities and properties in nature to be more *fundamental* than others. In admitting this hierarchical structure, neo-Aristotelians find themselves aligned with Fine and Schaffer in rejecting 'flat' Quinean conceptions of nature, which simply list the set of entities that exist according to some physical theory. In later chapters, we shall see how the notion of metaphysical grounding can be deployed in explaining phenomena like quantum entanglement (see Chapters 4 to 6).

*A powers ontology*
NA/II: Nature contains objects that exercise causal powers.

According to neo-Aristotelians, nature contains real potentiality to bring about change, which is irreducible to categorical structures that can be described without reference to change. There are physical objects that possess intrinsic and essential powers, according to their natures, and extrinsic and accidental powers, according to their environments (see Section 2.4). Causation is neither reducible to regularities among categorical properties, nor to transcendent laws of nature that somehow impose change upon nature. Rather, causal powers introduce an element of teleology, or natural intentionality, inasmuch as powers are *directed* toward their manifestations. In these respects, neo-Aristotelians agree with philosophers like Mumford and Marmodoro in rejecting 'categoricalist' Humean conceptions of nature. In later chapters, we shall see how powers can play a role in grounding the laws of quantum mechanics (see Chapter 6 & Chapter 9).

*Moderate realism*
NA/III: The fundamental objects of scientific inquiry have real natures, but natures are not universals.

For neo-Aristotelians, the natures of physical things are *immanent* within those things. Neo-Aristotelians do not appeal to non-immanent, non-natural universals to explain natural phenomena (see Section 1.2), nor do they appeal to transcendent entities or laws that extrinsically determine their behaviour. They regard mathematical models of the world, which characterise physical systems in terms of the properties of abstract mathematical structures, as idealisations which invariably involve a loss of empirical information. In later chapters, we shall see how the notion of 'metaphysical powers' that *unite* themselves to the matter of physical entities by *grounding* their powers supports a 'hierarchical' interpretation of quantum mechanics in which certain entities act according to their natures (see Chapters 6–9).

*Fundamental substances*
NA/IV: The world is composed of substances, which belong to natural kinds.

According to neo-Aristotelians, the basic building blocks of the physical world are substances: there is no change in the physical world that does not involve change in one or more substances. Schaffer's 'tiling constraint' requires that every physical part of nature should be wholly contained in the sum of its substances, and that no two substances should overlap [Schaffer, 2010]. Substances are entities that have an intelligible nature, *per se* unity, and fall under natural kinds. Natural kinds are neither subjective, conventional, nor (wholly) mind-dependent. They are neither abundant in nature, nor arbitrarily constructed. Rather, natural kinds are *sparse* (to use Lewis's terminology), and scientific inquiry seeks to discover what natural kinds exist and what powers are grounded in each kind. In later chapters, we shall consider a neo-Aristotelian model in which nature consists of a single cosmic substance (see Chapter 6), and an alternative model in which nature consists of a plurality of thermochemical substances (see Chapter 9).

ii. *Additional criteria for substances*

Finally, I should like to suggest some additional 'neo-Aristotelian' criteria that apply to a world that contains *robustly Aristotelian* substances:

*Active and passive powers*
FS/IV: Aristotelian substances are efficient causes which enter into causal relations with one another by exercising their active and passive causal powers.

*Metaphysical unity*
FS/V: Aristotelian substances are metaphysical unities in nature: they may have *integral* or *potential* physical parts, but they have no *actual* physical parts.

In later chapters, I shall theorise about how the causal powers of a substance are grounded in the nature of the substance (see Chapter 6 & Chapter 9).

## §2.6. General remarks

In this chapter, I discussed the role of metaphysics in the philosophy of science in providing a unified account of what nature is like (Section 2.1–2.2). I considered the use of metaphysical grounding for introducing different levels of being within nature (Section 2.3) and observed how an ontology of powers is consistent with a conception of scientific inquiry in which the sciences are concerned with uncovering truths about nature (Section 2.4). I also outlined some basic features of a 'neo-Aristotelian' approach to the metaphysics of science, which combines both the notions of powers and metaphysical grounding (Section 2.5).

Nonetheless, despite the increasing interest in the use of grounding and causal powers in contemporary philosophy,[15] few philosophers have engaged directly with the metaphysics of quantum theories from a 'neo-Aristotelian' perspective, or reconsidered the relationship between the old Aristotelian concepts of 'matter' and 'form' in the light of contemporary quantum mechanics. Whilst the concept of potentiality is now more widely embraced among philosophers, the micro-monist conception of matter as fundamental constituents with intrinsic physical properties (MM/I-II), which replaced the Aristotelian conception of matter as potentiality for substance (AH/I-III), has yet to receive any serious scrutiny (see Chapter 1).

In what follows, I shall discuss how quantum mechanics applies pressure to the classical micro-monist conception of matter as particles (or fields) with intrinsic physical properties, and will consider a recent proposal for a quantum micro-monist philosophy of nature that seeks to accommodate the phenomenon of quantum entanglement by offering an alternative conception of matter without physical properties. I shall identify a number of problems with this metaphysical model, and demonstrate how they can be redressed in the course of considering a succession of increasingly 'neo-Aristotelian' models of nature.

## Notes

[1]Crane, T., Aristotle Returns, First Things, 2018.

[2]Even in the Everettian interpretation, the scope of the superposition principle is limited by the interpretation: measurement outcomes may split across worlds, but perceptual states in each world are determinate.

[3]Concerning the irreducibility of QSM and the reality of the thermodynamic limit, see [Ruetsche, 2011], chapter 12.

[4]For example, see [Kim, 1966]. Temperature is not a characteristic of individual molecules, but of an equilibrium distribution. The distinction is apparent in the case of systems that are not at equilibrium, in which the molecules have a mean kinetic energy but the temperature is not well-defined.

[5]I mean *critical* with respect to what may be taken as 'received wisdom' or 'common sense'.

[6]Concerning the 'grounding challenge' to Quinean philosophy, see [Egerton, 2016].

[7]According to Schaffer's theory of 'priority monism', for example, the cosmos is a fundamental substance that grounds its integral parts [Schaffer, 2010].

[8]This modal necessity obtains because it is necessary that $2 + 2 = 4$, but not in virtue of the fact that it is snowing.

[9]Bacon denounced the 'frigid distinction of act and potency', claiming that 'single bodies have each a single and proper motion, and that if they participate in any other, then this results from an external cause'.

[10]This thought is sometimes expressed by the claim that Humeans are committed to the existence of natural properties that have hidden *quiddities*, although the modern use of this term differs from the scholastic use.

[11]For a more detailed discussion, see [Mayr, 2011, chps. 6-7].

[12]The concept of agency may be taken to have paradigmatic form in the case of human or creaturely agency.

[13]Mumford and Anjum defend the alternative view of *dispositional modality*, in which powers only 'tend' to manifest in a certain way. For criticisms of this view, see [Marmodoro, 2016].

[14]Not all Humeans agree: Handfield thinks such an account gets 'the order of explanation entirely the wrong way round' [Handfield, 2010, p.108]. His own form of 'Humean dispositionalism' [Handfield, 2008], however, is not without serious difficulties [Simpson, 2017].

[15]For recent anthologies, see [Simpson et al., 2017, Jacobs, 2017, Groff and Greco, 2017, Marmodoro, 2013c, Tahko, 2011].

# Part II

# The road to power monism

In Part I, I discussed how the Aristotelian 'hylomorphic' conception of nature, in which the physical world consists of substances composed of matter and form, was replaced by a micro-monist conception of nature, in which the physical world consists of a set of fundamental constituents with intrinsic physical properties (Chapter 1). I also discussed the rise of 'neo-Aristotelian' approaches within contemporary metaphysics, which deploy the notions of grounding and causal powers (Chapter 2).

In Part II, I shall explore how the phenomenon of quantum entanglement challenges the classical micro-monist conception of the world as consisting of particles (or fields) with intrinsic physical properties. I begin with a metaphysical model called 'Super-Humeanism', which attempts to update neo-Humean metaphysics to produce a quantum micro-monist model that is compatible with quantum mechanics. I discuss a number of problems with this model, and proceed to propose two models that modify Super-Humeanism in various ways: a semi-Humean model, which deploys powers but retains Humean laws; and a 'neo-Aristotelian' model, that deploys powers and the concept of metaphysical grounding. Part II consists of four chapters:

Chapter 3

# Matter without microphysical properties

*I would not call [entanglement] one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.*

– Erwin Schrödinger, *Naturwissenschaften*

## §3.1. The quantum revolution in microscopic physics

Erwin Schrödinger regarded quantum entanglement to be both 'the characteristic trait of quantum mechanics' and a revolutionary concept 'that enforces its entire departure from classical lines of thought' [Schrödinger, 1935a]. Many contemporary metaphysicians, however, have not concerned themselves with accounting for such phenomena, whilst some have been content to adopt instrumentalist approaches to quantum mechanics instead. It has been suggested, for instance, that the predictions generated by quantum mechanics should be taken as rational credences rather than objective probabilities [Healey, 2012]. In this thesis, I mean to adopt a broadly realist stance in which quantum physics is considered to be part of a tradition of scientific inquiry that is commensurate with the empirical tradition of Aristotle (see Section 1.2), the goal of which is to give true descriptions of nature:

*Assumption of inquiry: Scientific realism*
AI/I: Other things being equal, we should favour accounts that imply that our best physical theories, properly interpreted, are possibly true, independently of our preferences and practices.

Nonetheless, quantum entanglement poses a metaphysical challenge to the classical micro-monist conception of matter as consisting of particles (or fields) with intrinsic physical properties (MM/I-II). Indeed, certain philosophers of science, like James Ladyman, have argued that, in the light of quantum entanglement, naturalists should adopt 'structural ontologies' instead of 'substance ontologies', abandoning the traditional categories of ‘things’ that have intrinsic properties in favour of ‘ontic structures’ that are constituted solely by relations [Ladyman and Ross, 2007].

More recently, a refinement of this project has been advanced by Michael Esfeld, who has combined *ontic structural realism* with the *primitive ontology approach* to quantum mechanics (of which more later), putting forward a minimalist ontology of the natural world consisting of ‘matter points’ constituted by distance relations. According to Esfeld, it is not ‘things’ that must go, such as particles, but ‘physical properties’, like mass and charge, if metaphysicians are to succeed in accommodating quantum phenomena within a true account of nature [Esfeld, 2014a]. The matter of which the world is made is not *essentially* characterised by any of the micro-properties that our physical theories rely upon in order to represent change; rather, such properties are simply useful and informative ways of representing that change.

## §3.2. The problem of non-locality

In what follows, I shall consider some motivations for adopting an ontology of quantum mechanics *without* fundamental microphysical properties. To understand why philosophers like Esfeld and Ladyman assert that microphysical properties neither determine behaviour nor individuate physical objects, we must consider the role that the concepts of *non-locality*, *non-separability* and *holism* have played in these metaphysical debates. The phenomenon I wish to discuss concerns systems in which microscopic particles are said to be ‘quantum-entangled’. In such cases, the outcomes of measurements of physical ‘observables’ associated with each particle are correlated in such a way that the quantum state describing this system cannot be decomposed into the product of separate states associated with each particle.

For example, in the famous EPR experiment involving two particles, originally proposed as a thought-experiment by Albert Einstein and his associates in 1935 [Einstein et al., 1935], one particle is constrained to be ‘spin-up’ $|\uparrow\rangle$ when another is ‘spin-down’ $|\downarrow\rangle$, and vice versa, however far apart the two particles are spatially separated. Quantum mechanics permits solutions to the Schrödinger equation to be combined, allowing the system to be in a *superposition* of both states. The superposition, in this case, is the famous singlet state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2). \tag{3.2.1}$$

When a system is in the singlet state, there is a probability of 1/2 that we will observe particle 1 to be ‘spin up’, and particle 2 to be ‘spin down’; there is also a probability of 1/2 that we will observe particle 1 to be ‘spin down’, and particle 2 to be ‘spin up’. There are no other physically possible outcomes. The probabilities for these outcomes are obtained from the square modulus of the wave function that represents the quantum state: $|\psi|^2$.

Following Esfeld's discussion in [Esfeld, 2017], I shall briefly review how this entangled behaviour arises. Suppose two particles emitted from a common source fly off in opposite directions, and two experimenters (traditionally, 'Alice' and 'Bob') are suitably positioned to measure certain physical observables associated with each particle, once the two particles are sufficiently separated. In his ground-breaking discussion of quantum entanglement in 1964, the physicist John Bell formulated a theorem drawing a radical distinction between the local behaviour explained by classical physics and the non-local behaviour of systems governed by quantum physics [Bell, 1964]. In order to describe its implications more precisely, it will be helpful to introduce some notation.

Let $\phi_A$ specify the configuration of Alice's apparatus, and $A$ the outcome of her experiment; likewise, $\phi_B$ for Bob's apparatus, and $B$ for his outcome. Let $\lambda$ denote whatever in the past may have influenced the behaviour of the system that is being measured. In our example, $\lambda$ includes the physical state of the two-particle system, prior to measurement. The measuring apparatus in each case is a Stern-Gerlach device, in which a pointer has the possibility of being deflected up or down, and the configuration parameters are the two angles of polarisation of each device, $\phi_A$ and $\phi_B$. These parameters can be set at an appropriate angle for measuring vertical spin (that is, 'spin-up', or 'spin-down'), but can also be adjusted separately to produce a range of measurement outcomes. According to Bell, the principle of locality requires:

$$P_{\phi_a,\phi_b}(A|B,\lambda) = P_{\phi_a}(A|\lambda), \tag{3.2.2}$$

$$P_{\phi_a,\phi_b}(B|A,\lambda) = P_{\phi_b}(B|\lambda). \tag{3.2.3}$$

This formalisation can be read as follows: according to the principle of locality, the probabilities for Alice obtaining outcome $A$ can be fixed by conditionalising on the configuration of her apparatus $\phi_A$, and whatever in the past influenced its behaviour $\lambda$, such as the local properties of the particle she measures. Significantly, conditionalising on the configuration of Bob's apparatus, in a world in which locality holds, does not change the probabilities for Alice's outcome. This is also the case for Bob's outcome with respect to Alice's apparatus.

Bell's theorem demonstrates that the principle of locality is violated by the phenomenon of quantum entanglement. In this way, Bell problematised the correlations between spatially separated systems that are quantum-entangled for any physical theory in which the prospect for transmitting a signal that causally influences a physical system is limited by the speed of light. According to quantum mechanics, the probabilities for obtaining a measurement outcome in one part of the experiment depend on the outcome obtained in the other part of the experiment, in spite of the fact that the two measurement events are represented as 'spacelike separated' in the theory of special relativity.

To visualise the limits on causal signalling imposed by the theory of relativity, the mathematician Hermann Minkowski suggested imagining a flash of light, confined to a two-dimensional plane, which spreads out in a circle from an event $E$ at some time $t$ [Minkowski, 1908]. If we graph the growing circle using time as the vertical axis, we obtain a 'light-cone' for event $E$ that extends to include any past event $t' < t$ in which a signal could have been sent which would have time to reach $E$ and causally influence this event. However, any event which falls outside of the light-cone of $E$ is 'spacelike separated' from $E$, and cannot be causally related to $E$ by any mechanism:

*The superluminal ban on causal signalling*
SBS: The physical cause of a physical effect must lie within the past light-cone of its effect.

Since the measurement events in the two wings of the EPR experiment corresponding to $A$ and $B$ do not belong within each other's past light-cones, they are space-like separated. However, applying the 'classical' assumption that the behaviour of the particles can be explained by a local mechanism implies one set of measurement statistics, whereas quantum mechanics predicts another. Significantly, in the case of the EPR experiment, quantum mechanics predicts that the measurement statistics will depend on the relative angle between the two measuring devices, $\phi_A - \phi_B$. This fact is something that neither particle, considered separately, could possibly 'know' by means of any subluminal mechanism. Whilst the EPR experiment was originally intended as a *reductio ad absurdum* of quantum mechanics by Einstein, subsequent experiments – in particular, those of Alain Aspect in the 1980s [Aspect et al., 1982]) – are now widely regarded as having confirmed the statistics predicted by quantum mechanics and established non-locality as an empirical fact in the following sense:

*Quantum non-locality*
QNL: What happens at point $P$ in space and time depends not only upon what exists in the past light-cone of this event, but also upon what happens outside of its light-cone, at points in space separated from $P$ by a space-like interval.[1]

This behaviour is not merely a peculiarity of early pioneer quantum mechanics: it remains a puzzling feature of more sophisticated quantum field theories deployed by the Standard Model of particle physics, and is likely to remain a feature of any theory of quantum gravity. The *problem of non-locality* that contemporary realists face is the challenge of explaining the non-local measurement outcomes of quantum experiments, given the ban on superluminal signalling that applies to causal mechanisms in modern physics.

Yet there is more than one way to think about dependency relations. Non-locality might be construed as a form of *metaphysical* dependency, rather than a form of *causal* dependency (see Section 2.3), if we are willing to drop the assumption that quantum-entangled particles exist independently of one another.

## §3.3. Against microphysical properties

Since the 1980s, quantum-entangled systems have been widely considered by philosophers of physics to be *non-separable*, in the sense that the physical states of the sub-systems of a quantum-entangled system fail to determine the total state of the system as a whole (eg. [Howard, 1985], [Howard, 1989] and [Teller, 1986]). This in turn has suggested the need for some form of holism, in which the properties of a system depend in some way upon the whole system instead of being determined by the properties and relations of their parts (eg. [Healey, 1991]). Such a position, however, contradicts a common assumption among analytic metaphysicians, influenced by philosophers like David Lewis, concerning the status of physical properties:[2]

*Micro-property fundamentalism*
MPF: The physical properties of a macroscopic system supervene upon the intrinsic physical properties of, and relations between, the microscopic constituents of its supervenience base.

The contradiction between the thesis of micro-property fundamentalism and the fact of quantum non-locality turns on two mediating assumptions that are still widely held among analytic philosophers concerning the nature of physical properties:

*Classical metaphysical assumptions*
CM: The fundamental physical properties in the supervenience base are

1. spatiotemporally localised, and
2. causally related by a simple set of microphysical laws.

According to Lewis, for example: 'All there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another... We have geometry: a system of external relations of spatio-temporal distances between points... And at those points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated. For short, we have an arrangement of qualities. And that is all.' [Lewis, 1986, p.ix]. For neo-Humeans like Lewis, natural properties may be related within a system of laws, where a law expresses a regularity in their arrangement that constitutes a 'contingent generalization that appears as a theorem (or axiom) in each of the true deductive systems that achieve a best combination of simplicity and strength' [Lewis, 1973, p.73].

If micro-property fundamentalism (MPF) involves these 'classical' metaphysical assumptions (CM), then it implies the existence of a supervenience base composed solely of localised physical properties that are causally related by microphysical laws. Yet the fact of quantum non-locality implies, on the contrary, the non-existence of such a supervenience base, insofar as such laws and properties conform to the superluminal ban on signalling (SBS & QNL) [Maudlin, 2007, chp.2].

I shall take the fact of quantum non-locality as a starting point for my discussion, setting aside theories which attempt to explain away the appearance of non-locality.[3] Of course, one might acknowledge the fact of quantum non-locality, but deny the claim that the superluminal ban on signalling in modern physics applies to *all* causal mechanisms, by postulating the existence of a superluminal mechanical force. This force would have to act upon both wings of the EPR experiment such that the microphysical properties of both systems exhibit non-local correlations.

However, the notion of an additional ‘quantum force’ (typically associated with the work of David Bohm in the 1950s [Bohm, 1951, Bohm, 1952a, Bohm, 1952b]) has struck many physicists as contrived and implausible: such a force finds no analogue in classical mechanics, where the forces that couple particles and fields depend on the intrinsic properties of the particles in motion, and the introduction of a special mechanism to produce non-local quantum phenomena is *ad hoc*. Moreover, further experiments have continued to increase the lower-bound on the velocity at which such a mechanism would have to operate to produce the non-local correlations in the measurement outcomes of quantum-entangled systems [Salart et al., 2008, Cocciaro et al., 2011]. To the historian of science, such an attempt to salvage the framework of classical mechanics is more likely to evoke the spectre of Ptolemaic epicycles than the fabled cry of ‘Eureka’. I shall exclude this possibility by endorsing this second assumption about scientific practice:

*Assumption of inquiry: Ockham’s razor*
AI/II: Other things being equal, we should adopt the simplest scientific theory that explains the phenomena.

Yet if quantum non-locality is not to be explained away as mere appearance, and if Ockham’s razor is to be wielded against the hypothesis of a superluminal causal mechanism, then the contradiction between the fact of quantum non-locality and the thesis of micro-property fundamentalism leads to the following dilemma:

*Supervenience dilemma*
Either (i) micro-property fundamentalism is false, or (ii) the fundamental microphysical properties of a system are not spatiotemporally localised.

Wave function monists seize the second horn of this dilemma by regarding the wave function representing the quantum state as the more fundamental reality upon which the world of physical objects supervenes, and denying the assumption that the parts of a system are spatiotemporally localised (CM1). According to this approach, local properties belong merely to the theatre of experimentation and observation, to be recovered by finding something within the wave function that functionally corresponds to the pointer-like behaviour of our measuring devices.

Some wave function monists, for example, offer to restore the thesis of micro-property fundamentalism by identifying the wave function with a physical field that exists in the high-dimensional space in which the wave function is mathematically defined, whilst identifying the properties of this field with intrinsic qualities of the points in this mathematical space (see eg. [Loewer, 2016]). Such an approach has run into difficulties in its generalisation to quantum field theory [Myrvold, 2015]. Other wave function monists have suggested that the high-dimensional space of the wave function may be conceived as a physical property of four-dimensional space-time, whilst postulating the existence of 'branches' within the wave function from which innumerable 'macro-worlds' may be said to 'emerge' that realise every possible measurement outcome. The lack of any precise definition of a branch continues to frustrate any many-worlds account of the emergence of physical objects.[4] Nonetheless, in spite of their technical difficulties, various forms of wave function monism remain popular among philosophers of physics.

However, metaphysicians have raised fundamental objections. Tim Maudlin, recalling earlier arguments made by Bell, has notably argued that functional correspondence, by itself, is insufficient for securing a connection between the world described by quantum mechanics and the theatre of experimentation and observation [Maudlin, 2010, Bell, 1987b]. In order for there really to be a pointer on a measuring device, which has some probability of pointing up or down when we make a measurement, there must be some pointer-shaped configuration, which has the potential to evolve one way or another, corresponding to the possible positions of the pointer observed by experimentalists. If no pointers with possible positions really existed – that is, if the world of physical objects had no matter to give it being apart from the wave function – there would be nothing for the probabilities of the different measurement outcomes predicted by quantum mechanics to be *about*. This corresponds to what Maudlin identifies at *the problem of statistics* in [Maudlin, 1995, pp. 10-13] (see also [Price, 2010]).

By dissolving this distinction between the abstract model of quantum mechanics and the physical world that it is supposed to be modelling, wave function monism slides into obscurantism, shifting the theatre of experimentation and observation away from the world of space and time to a Pythagorean world of mathematical properties. Within the reified world of the wave function, neither scientists nor their measuring devices exist in reality, and there are no objective, non-perspectival facts about which way the pointers on their measuring devices are pointing. As Esfeld observes, such a strategy threatens to surrender a 'central tenet not only of common sense realism, but also of all working science' [Esfeld, 2014a]. It also leads to intractable problems in the philosophy of perception (for further discussion, see [Solé, 2013, p. 366], and [Belot, 2012, pp. 73-74]).[5]

In order to safeguard this assumption of scientific inquiry, I shall favour interpretations of quantum mechanics that straightforwardly affirm the existence of objects in physical space whose parts are spatiotemporally localised. I shall also favour interpretations in which scientific instruments are objects that register determinate measurement outcomes according to the predictions of quantum mechanics:

*Assumption of inquiry: Reality of objects in physical space*
AI/III: The objects of scientific inquiry are real and their parts are localised within a physical space that is distinct from any mathematical representation.

Suppose, then, we seize the first horn of the supervenience dilemma. In that case, we must abandon classical assumptions about how physical objects are fundamentally characterised (CM). Whilst classical mechanics could provide an account of the dynamics of objects in physical space that was empirically adequate for local phenomena, the phenomenon of quantum entanglement is incompatible with the notion that quantal properties, like spin, are intrinsic features of localised particles or fields. Moreover, the evidence of interference phenomena, such as the Aharonov-Bohm effect, and of other interferometry experiments, such as the COW experiment, suggests that 'classical' properties, like mass and charge, are best understood at the level of the wave function, rather than as intrinsic properties of particles [Brown et al., 1995, Brown et al., 1996]. In short, if we accept certain standard assumptions of scientific inquiry (AI/I-III), we have good reason to follow Esfeld in demoting microphysical properties from being fundamental to being (in some sense) derivative.

## §3.4. Entanglement and the measurement problem

Whilst non-separability implies that systems which are quantum-entangled will temporally develop together, embracing non-separability is not sufficient to solve the problem of non-locality [Henson, 2013]. In order to give an empirically adequate account of quantum entanglement, we must explain the determinate measurement outcomes in the EPR experiment [Esfeld, 2017]. To make these outcomes intelligible, we require an account of the dynamics of a quantum-entangled system that individuates its separate components and explains its non-local statistical correlations, without flaunting the ban on superluminal signalling (SBS).

Part of the challenge in achieving such an account is that the description of the world offered by standard quantum mechanics, taken at face value, seems obviously false. This is because the indeterminacy that it famously attributes to the microscopic realm of particles it likewise extends to the macroscopic realm of our measuring devices. Suppose, for example, we consider an electron in a Stern-Gerlach device, which is in the quantum state of spin-up $|\uparrow\rangle$ or spin-down $|\downarrow\rangle$. According to the generalised Born Rule, adopted in standard quantum mechanics, any *observable* of a device is associated with a quantum state that is subject to the laws of quantum mechanics, and in standard quantum mechanics any quantum state (or wave function) evolves according to the linear Schr̈odinger equation. I shall take the device as having been prepared in a quantum state that is suitable for making a measurement of vertical spin (that is, spin-up or spin-down), and will label this state $|\phi\rangle$ (it is typically taken as a many-particle wave function).[6] According to standard quantum mechanics, on registering the spin of the particle, the pointer on the detector is supposed to assume an appropriate final state:

$$|\uparrow\rangle\,|\phi\rangle \to |\uparrow\rangle\,|\phi_\uparrow\rangle \quad or \quad |\downarrow\rangle\,|\phi\rangle \to |\downarrow\rangle\,|\phi_\downarrow\rangle \tag{3.4.1}$$

The final state (on the right of the arrow) to which the total system evolves is one in which the pointer of the measuring device is either pointing up $|\phi_\uparrow\rangle$ or down $|\phi_\downarrow\rangle$, depending on the state of the particle.[7] A system that may be in one or the other of these states is described as a proper mixture, in which the different probabilistic weightings of the elements in this ensemble simply reflect our ignorance of the system's actual condition prior to completing the experiment. However, quantum mechanics permits a system to be in a superposition of both states:

$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right)|\phi\rangle \to \frac{1}{\sqrt{2}}\left(|\uparrow\rangle\,|\phi_\uparrow\rangle + |\downarrow\rangle\,|\phi_\downarrow\rangle\right) \tag{3.4.2}$$

In this example, the final state of the pointer on the device, as described by standard quantum mechanics, is neither up $|\phi_\uparrow\rangle$ nor down $|\phi_\downarrow\rangle$, but an indeterminate superposition with respect to its position, which is distinguishable in principle from a proper mixture by the phenomenon of quantum interference. What we observe, however, is a pointer that occupies one of its possible positions: in this case, the probability of either outcome is 1/2. The bare quantum mechanics delivers the correct statistics for the results of repeated measurements, which is predictively useful, but fails to secure a determinate outcome that corresponds to our experience, which is deeply perplexing.

This is the famous *measurement problem* (or, the 'Schrödinger-cat paradox', devised by Schrödinger [Schrödinger, 1935b]). More precisely, it corresponds to what Maudlin identifies as the *problem of outcomes* [Maudlin, 1995, pp. 7-10]. In order to solve this problem, without abandoning the assumption of realism (AI/I), we must find a way to connect the formalism of quantum mechanics to some reality that exists independently of our preferences and practices, which fixes the facts about the measurement outcomes of quantum experiments and recovers the correct quantum statistics. However, since the wave function that solves the Schrödinger equation only encodes probabilities for local observables that fail to commute with one another (via the Born Rule, which is supposed to hold universally in standard quantum mechanics), such an account faces a dilemma posed by Bell [Bell, 1987b]:

> *Nomological dilemma*
> Either (i) the standard (linear) Schrödinger dynamics is wrong, or (ii) standard quantum mechanics is incomplete.[8]

All things considered, only two schools of interpretation seem empirically adequate: either we must seize the first horn of the dilemma by adopting some non-linear modification of the Schrödinger dynamics, which allows the wave function to 'collapse' and produce a definite outcome, or seize the second horn of the dilemma by adopting 'additional variables' and supplementing the Schrödinger dynamics with a non-linear dynamics for their temporal development. According to Maudlin: 'only collapse theories and hidden variables theories have a chance of succeeding, and, of the latter, the modal interpretations fail' [Maudlin, 1995, p.7]. In modal interpretations, the wave function is supplemented by a 'value state' that supports additional properties but has no separate dynamics, yet these face what Maudlin calls the *problem of effect*, since the outcome of measurements afford no predictive power for the future behaviour of the system [pp.13-4]. In a micro-monist world in which all the measurable properties of a system are *quantal properties* determined by the universal wave function (via the Born Rule), the two standard approaches to solving the problem of outcomes are the GRW theory and Bohmian mechanics.

i. *The GRW collapse theory*

The GRW model suggested by Giancarlo Ghirardi, Alberto Rimini and Tullio Weber in 1986 [Ghirardi et al., 1986] seizes the first horn of the nomological dilemma: it seeks to incorporate the text-book 'collapse' of the wave function proposed by Heisenberg, by modifying the Schrödinger equation for the wave function $\psi$ to include a stochastic mechanism, non-linear in $\psi$, which brings about its spontaneous localisation. Whilst microsystems composed of a few quantum-entangled particles seldom localise spontaneously (the collapse rate being of the order of $10^{16}$ seconds), macrosystems composed of many quantum-entangled particles localise in a very short time (in about $10^{-7}$ seconds, for a system of $10^{23}$ particles). Any localisation in one element of a quantum-entangled system precipitates the localisation of the other elements, hence the collapse rate of macroscopic objects increases according to the number of their microscopic constituents [Clifton and Monton, 1999, p.700-1]. (For a substantial review of 'dynamical reduction' schemes of this kind, see [Bassi and Ghirardi, 2003].)

In more recent discussions of the GRW theory, it has been suggested that the wave function should be supplemented with a 'matter-density' field that evolves in physical space, and stochastic localisations of the wave function should be understood as corresponding to spontaneous contractions in the distribution of matter-density [Ghirardi et al., 1995]. (For a relativistic version of GRW theory, see [Tumulka, 2006].) This interpretation affirms the reality of objects in physical space and specifies what the probabilities of quantum mechanics are about (AI/III). However, the GRW theory comes with a theoretical cost: the spontaneous collapse mechanism that it posits to explain measurement outcomes is not observed to take place in nature, and the stochastic terms that it adds to the Schrödinger equation lack any underlying justification. However, underlying theories for alternative collapse mechanisms are being actively investigated [Bassi et al., 2013]. I shall consider a plausible example of an alternative collapse mechanism later in this discussion, which appeals to the thermal properties of complex physical systems (see Chapter 7).

ii. *The de Broglie-Bohm pilot-wave theory*

The pilot wave theory of de Broglie and Bohm [de Broglie, 1928, Bohm, 1951, Bohm, 1952a, Bohm, 1952b], which has been championed by Detlef Dürr, Sheldon Goldstein and Nino Zanghí under the name of 'Bohmian mechanics' since the 1990s [Dürr et al., 1992, Dürr et al., 1997], seizes the second horn of the nomological dilemma: it leaves the Schrödinger dynamics of the wave function $\psi$ untouched, whilst positing a configuration of $N$ particles that follow a guiding equation that specifies each particle's velocity. (For recent textbook studies, see [Holland, 1993, Dürr, 2009, Dürr et al., 2012, Bricmont, 2016].) The particles, in this case, have well-defined positions at each moment of time.

The equation of motion – or 'guiding equation' – is first-order with respect to time $t$ and non-linear in $\psi$, determining a velocity field $v_i^\psi$ that does not require the particles to have intrinsic physical properties, but only to have determinate relative positions. (The particles are attributed gravitational mass, but the COW experiment suggests that mass delocalises over the wave function [Brown, 1996].) There is no need for a second-order formulation involving accelerations rather than velocities, in order for this theory to be explanatory, hence there is no need to maintain the framework of classical mechanics and posit a dubious 'quantum force'. According to Bohmians, the Schrödinger equation and guiding equation together comprise the non-classical dynamics of a particle configuration that exists independently of our observations, and the wave function is given the nomological role of inducing a velocity field that choreographs the trajectories of all the particles through physical space. This universal wave function does not collapse. (From this point, 'Bohmian mechanics' will refer to this first-order formulation, unless otherwise stated.)

Agreement with the Born Rule is typically secured via the quantum equilibrium hypothesis: specifically, if the initial configuration of the particles at $t$ may be supposed to be randomly distributed with a probability distribution $\rho(t = 0) = |\psi_{t=0}|^2$, then it follows as a consequence of the Schrödinger equation and Bohm's law of motion that this relationship will hold at some later time $t > 0$ for the distribution $\rho(t) = |\psi_t|^2$. Since the theory allows in principle for non-equilibrium solutions, $\rho \neq |\psi|^2$, this restriction to quantum equilibrium has generally been taken as a postulate [Dürr et al., 1992].[9] This introduces the elements of randomness and indeterminacy essential to quantum mechanics. Although the particles have determinate positions, we cannot know where all of the particles are, and must resort to the probabilities of quantum mechanics to make predictions. Nonetheless, the physical state of the world at time $t$ is completely specified by both the wave function and the positions of the particles: $(\psi, \{\mathbf{Q}_1, \ldots, \mathbf{Q}_N\})_t$.

According to this interpretation of quantum mechanics, indeterminate superpositions, such as the singlet state in the EPR experiment, are not fundamental features of reality: rather, every macroscopic object is composed of a determinate configuration of microscopic particles. These particles occupy definite positions at any time $t$, and evolve according to a deterministic law of nature. The probabilities encoded in the wave function are thus *epistemic* probabilities about their trajectories. Whilst the motion of Bohmian particles may seem random, the appearance of randomness is an artefact of treating physical systems in isolation: the actual velocity function for the global configuration is defined in terms of a universal wave function, and depends upon the positions of all of the particles. Bohmian particles do not move like Billiard balls in classical mechanics, which travel in straight lines until disturbed by an external force, but wobble their way through space in conformity with the velocity field $v^{\psi}$ induced by the universal wave function. The 'non-locality' of Bohmian mechanics is manifest by the fact that the velocity of any one particle depends on the instantaneous positions of all of the other particles.[10]

### iii. *Decoherence*

Nonetheless, in order for there to be any measurements of sub-systems of particles, such as the quantum-entangled system containing the two particles that feature in the EPR experiment, it must be possible for the pointers on a measuring device to *represent* something about this sub-system. In order for this representation to have empirical content, there must be some specifiable correlation between the states of the measuring apparatus, and the states of the system that is being measured. This relation is typically supposed to obtain in quantum mechanics through the process of decoherence, through which sub-systems of particles emerge whose behaviour approximate classical (Newton-Maxwell) laws.[11]

In a world in which the quantum dynamics depends upon a universal wave function, a measuring device is not an isolated entity, but is continually interacting with an environment composed of a swarm of particles, such as air molecules and photons. According to decoherence theory, this has the effect of making large-scale superpositions indistinguishable in practice from proper mixtures, in which the entangled state of the total system – enlarged to include the particle being measured, the measuring device, and the global environment – determines for the measuring device, for all practical purposes, a mixture that consists of different possible pointer positions.[12] Decoherence is the process of obtaining this mixture for any physical system that is immersed in an environment with many more degrees of freedom than itself. When the process of decoherence occurs in a physical system, such as a system composed of a measuring device and the sub-system of particles that it is supposed to be measuring, its quantum dynamics can be described in practice using an effective wave function, rather than the universal wave function.[13]

Decoherence theory, by itself, is not sufficient to account for the *actual* measurement outcomes of a quantum experiment. When combined with Bohmian mechanics, however, which posits a set of facts about the positions of all the particles, decoherence theory implies that the actual measurement outcome will be determined for all practice purposes by facts about *both* the microscopic positions of the particles composing the sub-system *and* the particles composing the measuring device(s), however far apart they may be separated. Thus Bohmian mechanics, unlike classical mechanics, offers an account of the non-local correlations between the outcomes of the EPR experiment: on the one hand, the pointers on the two measuring devices, which point either up or down, are composed of two localised arrangements of particles that are separated in physical space, as in classical physics; on the other hand, the non-local correlations in their measurement outcomes are due to the fact that fixing the configuration parameter in one part of the experiment, either $\phi_A$ or $\phi_B$, will influence the trajectory of the particles in both parts of the experiment, because the particles are governed by the *same* wave function.

The measurement problem, as described above, does not arise for Bohmian mechanics, in which the fundamental description of a physical state, before making a measurement, involves a single configuration of local constituents, and after measurement, includes the values of local variables that register the actual result. Yet I note here on passing that the theory of decoherence, upon which Bohmian mechanics relies, is hardly beyond questioning. It assumes, for instance, that the pointers of our measuring devices are rigid, solid bodies, although there are difficulties in accounting for the emergence of solid bodies from a finite set of particles (see Chapter 7). It also assumes (implausibly) that the environment of a system may be characterised by a many-body wave function that is subject to unitary time evolution (a subject I will take up again in Chapter 9). I shall defer these points, however, for the sake of argument.

## §3.5. A NOMOLOGICAL WAVE FUNCTION

From a philosophical standpoint, we can identify two levels of interpretation of a theory like quantum mechanics: the first requires us to take a position on the measurement problem and the quantum dynamics, which goes beyond the empirical data. Yet this is only a partial interpretation: a *metaphysical model* is also needed in order to specify an ontology of entities that exist in the world that exist independently of our preferences and practices,[14] and to enable a *semantic interpretation* of quantum mechanics, in which the theory may be understood as making truth claims about these entities. I shall be concerned primarily with the latter in this thesis.

In recent years, the GRW theory and Bohmian mechanics have been deployed by philosophers of science as part of a ‘primitive ontology approach’ to quantum mechanics, which seeks to provide a realist interpretation of quantum mechanics that avoids the problem of non-locality [Allori et al., 2008, Esfeld, 2014b]. This approach is inspired by Bell’s concept of ‘local beables’ [Bell, 1987b, chp.7] (whilst the term ‘primitive ontology’ originates in [Dürr et al., 2012, chp.2], originally published in 1992). Those who adopt this approach reject the notion that one can ‘read off the ontology’ of a physical theory from its mathematical structure, but maintain that all the empirical data constituting our evidence for quantum mechanics – such as the positions of pointers, etc. – concern a distribution of matter in three dimensional space or four-dimensional spacetime. The various properties that appear in the mathematical formalism of a physical theory represent a law of nature describing the temporal development of the matter. They enter into the physical theory through their nomological role, but are not part of the primitive ontology.

A primitive ontology approach to quantum mechanics aims to account for the determinate measurement outcomes of scientific experiments, like the EPR experiment, and more generally the macroscopic objects upon which scientists depend, by offering an account of the empirical content of a physical theory that is exhausted by its statements about the primitive ontology [Maudlin, 2019]. In the GRWm model, for example, the primitive ontology consists of a *matter-field* (or, gunk), and the formalism describes the spread and spontaneous contraction in its ‘matter density’ [Ghirardi et al., 1995].[15] This distribution of matter is described by a field equation that depends on the wave function. In the Bohmian interpretation of quantum mechanics, by contrast, the primitive ontology consists of *particles* (or, atoms), and the formalism specifies a law describing their trajectories through space. This law also depends upon the wave function. The matter in these ontologies is ‘primitive’ in more than one sense: first, it cannot be read off the formalism of standard quantum mechanics, but is put forward for the sake of empirical adequacy; secondly, it is a ‘primitive stuff, *materia prima*, having no physical properties at all’ [Esfeld et al., 2017, p.135].

However, a difficulty arises for philosophers who reject wave function realism and embrace a primitive ontology of matter, because the wave function at time $t$ does not supervene upon the configuration of matter at time $t$ [Suárez, 2015]. Rather, the wave function itself evolves through time, according to the Schrödinger equation, whilst two matter configurations that are identical at time $t$ may have wave functions that differ. In that case they will diverge at time $t' > t$. Barring speculative claims about how a theory of quantum-gravity might determine the wave function,[16] this raises a third dilemma for those who adopt a primitive ontology approach:

*Truthmaker dilemma*
To account for the truth of the Bohmian law of motion (or the GRW field equation), either we must appeal to (i) some entity in *addition* to the primitive matter, or (ii) the whole distribution of primitive matter for *all time*.

Suppose we attempt to take hold of the first horn of this dilemma by adding relations of necessitation, *a la* Armstrong, that somehow cause the particles to move in a certain way. According to the Armstrong-Dretske-Tooley conception of lawhood, we may think of a law of nature as being a primitive second-order relation between universals that brings about change by natural necessity (see [Dretske, 1977, Armstrong, 1983] and [Tooley, 1977, Tooley, 1987]).[17] Yet there are two difficulties here. First, a law of motion that includes the wave function as a nomological parameter, rather than a physical entity, cannot be construed simply as a relation between the positions of particles, since the wave function is subject to change at each moment, whereas the Armstrong-Dretske-Tooley conception of lawhood takes the temporal universality of laws for granted. Secondly, the particles in the primitive ontology do not have fundamental physical properties that could instantiate necessitation relations, since their properties depend on the wave function. It seems a distinct law would have to be formulated for every contiguous pair of configurations (cf. AI/II).

Suppose we refuse to expand the primitive ontology and seize the second horn of this dilemma instead. According to the Mill-Ramsey-Lewis conception of lawhood, we should think of generalisations as laws if and only if they are axioms in the best system that balances strength and simplicity in deriving the facts (see [Ramsey, 1978], [Lewis, 1973, pp. 73-75] [Lewis, 1987, postscript] and [Mill, 1875, Book III Chapter IV]). Such an account is compatible with a nomological interpretation of the wave function in which it is part of the best systems account of the facts, where the initial value of the wave function $\psi(t = 0)$ is fixed by the facts about the whole distribution of matter for all time (see [Miller, 2013], [Bhogal and Perry, 2017] and [Chen, 2018]).

In classical neo-Humean metaphysics, this mosaic of facts consists of intrinsic physical properties instantiated at different points in spacetime. However, as Esfeld observes, 'there is something new in quantum non-locality' that calls for a break with this neo-Humean ontology of sparse natural properties [Esfeld, 2017] (cf. [Miller, 2013]). For Bohmian primitivists, like Esfeld, this break consists in replacing varying Humean qualities with the single, uniform 'quality' of position. In short, some spacetime points are occupied by particles, and others are not. And that is all. I shall consider a 'Super-Humean' metaphysical model that takes this approach to the ontology of nature in the following chapter.

## §3.6. General remarks

In this chapter, I have discussed how the quantum revolution overthrew the classical micro-monist picture of nature, replacing the image of a world composed of particles (or fields) with intrinsic physical properties with a world in which microphysical properties are determined at the level of a wave function that is attributed to a quantum system as a whole. This revolution gave rise to the problem of non-locality (Section 3.2), which is the problem of explaining the outcomes of the EPR experiment given the superluminal ban on signalling in modern physics. In seeking to come to terms with this problem, I rejected the notion that microphysical properties are fundamental but non-localised (Section 3.3).

*Desideratum: Matter without microphysical properties*
DD/I: Other things being equal, we should favour metaphysical accounts in which microphysical properties are not fundamental.

I then offered considerations in favour of a primitive ontology approach to Bohmian mechanics (Section 3.4), in which matter consists of featureless particles, and the wave function may be conceived as part of a law which determines their trajectories (Section 3.5).

Nonetheless, in order to specify the supervenience base of the Bohmian law of motion, we need to establish what counts as a 'particle' in nature, and how these particles follow continuous trajectories through space. In the following three chapters (Chapters 4–6), I shall consider a sequence of metaphysical models which offer rival accounts of the supervenience base of the Bohmian interpretation of quantum mechanics. All three of these accounts seek to accommodate the phenomenon of quantum entanglement without departing from standard assumptions of scientific inquiry (AI/I-III). The first is a Humean model recently proposed by Michael Esfeld (Chapter 4). This model seeks to correct the neo-Humean metaphysics of Lewis by dispensing with his ontology of sparse natural properties.

## Notes

[1]This formulation is adapted from [Esfeld, 2017].

[2]Eg. Lewis's doctrine of Humean Supervenience.

[3]Such arguments rescind a common assumption of scientific inquiry: namely, that the settings of our measuring device are independent of the prior state of the measured system. (See [Esfeld, 2017], p. 2332.)

[4]The 'Oxford Everettians' have attempted to provide a quasi-rigorous definition of 'branches'. For a critique of this 'many-worlds' approach, see [Koons, 2017].

[5]Belot writes (adapting Jane Austin): "It is a truth universally acknowledged that an approach to understanding quantum mechanics is acceptable only if it allows us to construct models of the sort of experiments that provide evidence in favour of the theory" [Belot, 2012].

[6]I shall question this representation in Chapter 7. For an alternative view of the measuring device and the system's environment, see [Drossel and Ellis, 2018].

[7]For simplicity, I assume the measurement does not disturb the particle's spin eigenstates.

[8]In Bell's own words: 'Either the wave function, as given by the Schrodinger equation, is not everything, or it is not right' [Bell, 1987b].

[9]This move has sometimes been criticised as being 'artificial' [Valentini, 2019].

[10]Concerning relativistic versions of Bohmian mechanics, see [Dürr et al., 2014].

[11]For a helpful introduction to decoherence that avoids common misconceptions, see [Butterfield, 2001].

[12]As Bohm explains, the wave packets corresponding to different eigenvalues of the observable will cease to overlap in the space of relevant coordinate of the apparatus [Bohm, 1952b, p.181].

[13]We may think of the environment as 'measuring' the experiment.

[14]Or 'beables', in Bell's terminology.

[15]Alternatively, in the GRWf model, the primitive ontology consists of 'flashes', which are the collapse events [Bell, 1987a].

[16]It is sometimes claimed that the wave function is static, based on the time-independence of the Wheeler-DeWitt equation (the analogue of the Schrödinger equation in quantum gravity).

[17]Although each of these philosophers has his own view about laws of nature, it is generally recognised that they share a common core.

Chapter 4

# Super-Humean matter points

*Everything should be made as simple as possible, but not simpler.*

– Attributed to Albert Einstein.

## §4.1. Objects and structure

In the previous chapter, I introduced the *problem of non-locality* posed by the phenomenon of quantum entanglement, which is the challenge of explaining the non-local measurement outcomes of quantum experiments, given the superluminal ban on signalling in modern physics. Following Ladyman and Esfeld, I suggested that such phenomena gives us good reason to abandon the 'classical' micro-monist conception of matter as consisting of particles (or fields) with intrinsic physical properties [Ladyman and Ross, 2007, Esfeld and Deckert, 2017].

The primitive ontology approach to quantum mechanics embraced by Esfeld offers an account of quantum phenomena that preserves a single world of objects that exist in physical space, but abandons the thesis of micro-property fundamentalism (MPF). According to Bohmian primitivists, like Esfeld, a solution to the problem of non-locality can be secured in terms of a distribution of particles that lack intrinsic physical properties, if their trajectories are specified by the Bohmian law of motion. We nonetheless require a metaphysical account of how the featureless particles composing this configuration are supposed to be *individuated* (in other words, of what grounds the individuality and mutual distinctness of these basic entities).

In this chapter, I offer some critical reflections on Esfeld's 'Super-Humean' metaphysical model, which combines the primitive ontology approach to quantum mechanics (discussed in Chapter 3) with *ontic structural realism* in order to specify the nature of these particles and provide a supervenience base for this Bohmian law. Since the late 1990s, many philosophers of science have considered some form of structural realism to be the most tenable kind of scientific realism, persuaded by John Worrall of its power to break the tension between the famous 'no-miracles argument' for realism and the 'pessimistic meta-induction argument' for anti-realism [Worrall, 1989]. According to contemporary proponents of ontic structural realism, like French and Ladyman, these structures are best described within a model-theoretic approach to scientific theories [French and Ladyman, 2003] (discussed further in Chapter 8). On this view, the change in two quantum-entangled systems, such as the two particles in the EPR experiment, is explicable in terms of the change in the relations in which they stand. A suitable ontic structure, in this case, is one that:

OS1: does not supervene on the physical properties of the objects it relates, and

OS2: does not require the objects it relates to have intrinsic physical properties.

For ontic structural realists, there are no objects with intrinsic physical properties; in fact, there is nothing more to being an object than the relations in which it stands. The notion of ontic structure thus integrates the concepts of holism and non-separability (discussed in Chapter 3) by allowing objects to be individuated solely by their relations.

## §4.2. Local matter points

However, ontic structural realism, by itself, does not explain the non-local measurement outcomes of the EPR experiment, since it does not provide an account of what instantiates this structure and constitutes these measurement outcomes, to which the theory of quantum mechanics may be said to refer [Pylkkänen et al., 2015]. Nonetheless, according to Esfeld, it can supply the conceptual resources needed to solve the problem of non-locality when it is combined with the primitive ontology approach to quantum mechanics [Esfeld, 2012]. Esfeld's ontology may be defined using three axioms:[1]

*Super-Humeanism*

SH1: There are distance relations that individuate *matter points*.

SH2: There is a cosmic substance, composed of all the distance relations, of which the matter points are integral parts.

SH3: The matter points are the substrate of all physical change; it is the distances between them that change.

The primitive ontology consists of the 'matter points'. The ontic structure consists of the 'distance relations'. The matter points do not exist over and above this structure, since there is nothing more to being a matter point than its standing in certain distance relations. However, the world is not made of relations without relata: the matter points may be said to instantiate this structure because they are constituted by these relations [Esfeld and Lam, 2010].[2] This model is called 'Super-Humeanism'.

### i. *Matter*

For Esfeld, 'matter points' comprise the primitive substrate of all physical change. However, this matter is not to be confused with a bare, Lockean substrate. Rather, Esfeld adopts a 'Cartesian characterization of matter in terms of spatial extension' [Esfeld et al., 2017, p.140]. The decision to cash out the nature of matter in terms of matter points is supported by three considerations [Esfeld and Deckert, 2017].

First, Esfeld claims that our experimental evidence for the truth of quantum mechanics is always 'evidence of discrete objects (i.e. particles) from dots on a display to traces in a cloud chamber' [p.5]. This being the case, any empirically adequate account of quantum phenomena must be expressible in terms of the behaviour of a spatial distribution of matter. Secondly, physical properties do not determine the temporal development of a quantum-entangled system. According to Esfeld, the properties we attribute to physical objects are nothing more than a simple and informative means of representing change [p.7]. Thirdly, if the world contains distinct physical objects, it is necessary that there should be some type of world-making relation in virtue of which they compose a single world together. According to Esfeld, distance relations are as good a candidate as any for these world-making relations, as long as they are not tied to a particular geometry [p.10].

The minimalist character of Super-Humeanism is embodied in the claim that these world-making relations also constitute physical objects and specify the nature of matter. Esfeld writes: 'Its being part of what is minimally sufficient to obtain an ontology of the natural world that is empirically adequate is the best argument for an ontological commitment' [p.3]. The Super-Humean shuns any ontological commitment to fundamental physical properties, or any additional metaphysical structure besides distance relations. Super-Humeans rely upon the regularity account of relational spacetime developed by Huggett, in which the geometric structures deployed in Newtonian mechanics or the theory of Special Relativity are regarded merely as useful constructs for representing the change in the particles' distance relations, and as having 'no reality beyond their assumption by the laws' [Huggett, 2006, p.57].[3]

Likewise, the Super-Humean shuns any fundamental commitment to physical fields as the mediators of particle interactions. Although the concept of the field has been successful as an *effective* device for providing simple and informative descriptions of subsystems, physical fields are subject to a self-interaction problem in classical electrodynamics, and an ultra-violet divergence problem in quantum field theory, for which there appear to be no satisfactory solutions [Lazarovici, 2017]. Interactions in classical electrodynamics can be represented in physics without reference to fields using Wheeler-Feynmann theory, however, whilst particle creation and annihilation in quantum field theory may be worked out in terms of permanent particles using the Dirac sea model [Deckert et al., 2019].

ii. *Substances and entities*

In adopting an ontology of matter points without physical properties, Super-Humeans reject the classical micro-monist picture of nature, discussed in Chapter 3, in which the world consists of particles and fields with intrinsic physical properties that are picked out by our best physical theory. On the one hand, Super-Humeans affirm that there *is* a set of microscopic particles that compose all the macroscopic objects. A scientist perceives a pointer on a macroscopic instrument, such as a Stern-Gerlach device, for example, because there are particles arranged pointer-wise. On the other hand, Super-Humeans insist that these particles lack any intrinsic properties, and are *holistically individuated* by the distance relations in which they stand.

According to Esfeld, if we take Schaffer's theory of 'priority monism' to be merely a verbal re-description of the structural individuation of physical objects [Schaffer, 2010], in which ontological independence is taken as the criterion for something being a substance, Super-Humeanism should be cast as a form of priority monism, in which the microscopic particles are grounded in one fundamental substance; that is, in the cosmos as a whole [Esfeld, 2019, p.4]. A Super-Humean cosmos is thus an *integrated whole* (G1), rather than the mereological sum of its physical parts, and the particles that compose it are *interdependent entities* (G3) (see Section 2.3).

On this view, we should consider the various local 'substances' that are studied by the empirical sciences – such as charged electrons, chemical molecules, or organisms – as useful constructs that are partly grounded in our explanatory interests. The physical properties with which they are endowed in scientific descriptions of their behaviour are simply useful and convenient ways of representing change in certain parts of the global particle configuration. According to Super-Humeans, the world is not, in fact, objectively carved into separate substances with intrinsic properties. We subjectively carve them out of the cosmos as a whole.

iii. *Laws of nature*

In order to explain how physical systems change through time, however, such that a pointer on a Stern-Gerlach measuring device may change from pointing up to pointing down, for example, Esfeld is compelled to expand his supervenience base beyond matter points. Since distance relations are supposed to establish the order of what coexists in nature, he takes up Leibniz' relationalist definition of space. Since these distance relations constitute particles that change their positions, he follows Leibniz in conceiving time as the order of change. Esfeld must therefore sort his supervenience base into an infinite number of time-slices by imposing a linear ordering, in which each time-slice contains a complete assignment of distance relations between all of the matter-points that exist at that time. To give a direction to this linear ordering, which explains why one time-slice follows another, he must also include a *primitive arrow of change* (of which more later).

The Humean character of Super-Humeanism is embodied in the claim that any change in a physical system must supervene upon a Humean mosaic of matter points, where one configuration of matter points has no necessary connections with another. Esfeld writes: ‘everything else in the natural world supervenes on that mosaic in the sense that it comes in as a means to describe that change’ [p.8]. To account for the truth of the Bohmian law of motion, Esfeld adopts the Mill-Ramsey-Lewis account of lawhood, in which a regularity only qualifies as a law of nature just in case it is an axiom in the ‘best system’ that balances strength and simplicity in deriving the facts about how matter points are distributed in every time-slice.[4] The truth of the Bohmian law of motion is wholly determined by the spatial distribution of the matter points for all time, whilst the wave function of quantum mechanics is simply part of the Bohmian representation of this law of nature.

### iv. *Physical properties*

Whilst physical properties are not part of the primitive ontology, they are nonetheless indispensable for representing causal interactions between physical sub-systems, and formulating predictions for the behaviour of objects picked out by their physical properties. For example, when Alice transmits the results from her wing of the EPR experiment over the internet to Bob, physicists explain how he acquires this information by means of a causal mechanism involving the electromagnetic properties of the fibre-optic cables running between them. Yet Super-Humeans have reasons to believe that such mechanisms are not fundamentally characterised by microphysical properties that determine the way in which they behave. Rather, Super-Humeans seek to supplant the Humean mosaic of sparse natural properties with a changing configuration of distance relations. If we adopt Super-Humeanism, however, we can replace the thesis of property micro-determination with an alternative thesis:

*Holistic property determination*
HMD: The physical properties of a system are grounded on nothing less than the total distribution of matter points for all time.

Super-Humeans treat physical properties in the same way that classical neo-Humeans treat causal powers: just as powers are merely conceptual decorations, according to Lewis, so physical properties are not objective and intrinsic features of reality, according to Esfeld. Rather, we should think of them as useful and informative ways of representing parts of the changing global configuration of matter points. Whilst the laws of classical physics may be deemed explanatory, insofar as they are general principles that support counterfactuals, they should be distinguished from the Bohmian law of motion according to their scope of application. Super-Humeans regard the truth of the Bohmian law (or something like it) to be universal, inasmuch as it is taken to hold everywhere for all time, but regard the truth of classical laws to be scale-dependent, inasmuch as their domain is restricted to causal interactions within large systems of particles. Such systems may be more effectively described using suitable coarse-grained representations according to our explanatory interests.

v. *Advantages of Super-Humeanism*

Super-Humeanism, unlike the neo-Humeanism of David Lewis, offers a simple account of non-local quantum phenomena in terms of a holistic law of nature, which supervenes upon and is wholly made true by a linearly ordered set of time-slices composed of matter points. Furthermore, by adopting a primitive ontology of matter, Super-Humeanism is able to circumvent a common objection to classical neo-Humeanism. This objection involves the claim that, since the identity of a Humean property must be independent of the identity of whatever causal roles it may enter, Humean metaphysics is committed to the existence of fundamental properties that possess a hidden quiddity (or 'primitive thisness'). Insofar as the existence of quiddities is taken to be implausible, neo-Humeanism comes at a theoretical cost. Moreover, its commitment to quiddities is pragmatically inconsistent with a realist conception of scientific inquiry (see Section 2.4).

Esfeld is able to bypass these objections, however, by making the 'Super-Humean' move of eliminating all of the causally redundant and unknowable qualities that featured in classical neo-Humean metaphysics [Esfeld, 2014a]. According to Super-Humeans, physical properties are neither fundamental constituents, nor intrinsic features of spacetime: they are nothing more than a simple and informative means of representing change in the distance relations between microscopic particles. Likewise, by affirming the existence of individual matter points, Super-Humeanism also avoids some of the objections commonly raised against ontic structural realism (for instance, see [Briceño and Mumford, 2016]). Nonetheless, in attempting to maintain a Humean ontology of microscopic particles that is compatible with quantum mechanics, without invoking an ontology of sparse natural properties, Super-Humeanism creates some metaphysical problems of its own.[5]

## §4.3. The symmetric worlds problem

My first objection concerns an *implausible modal commitment* that follows from its structuralist conception of matter.[6] I shall argue that it leads to the contradiction that distinct particles in symmetric configurations are in fact identical.

i. *Argument*

This argument turns on the claim that, if Super-Humeanism is true, then it is metaphysically impossible that two distinct particles could be constituted by the same set of distance relations. In other words, Super-Humeanism is committed to the principle of constituent identity:

*Super-Humean principle of constituent identity*
PCI: If particle 1 is constituted by the same set of distance relations as particle 2, then particles 1 and 2 are identical to each other.

However, the principle of constituent identity entails a controversial principle:

*Leibniz' principle of the identity of indiscernibles*
PII: If object $O_1$ has a property if and only if object $O_2$ does too, then $O_1$ and $O_2$ are identical.

This claim is not to be confused with Leibniz's law, which is often referred to as the principle of the indiscernibility of identicals. According to this law, where there are instances of incompatible properties, there must correspondingly be distinct objects. Since the cosmos counts as an integral whole for Super-Humeans, Leibniz's law may be restricted to its integral parts: where there are instances of incompatible properties, there should correspondingly be distinct integral parts. (PII) is both logically independent of Leibniz's law, however, and more controversial: the sparser one's theory of constituents, the easier it is for objects to be indiscernible, and hence the easier it is to satisfy the identity condition imposed by (PII). In a sparse ontology, there are fewer properties that can explain the fact of an objective resemblance between two or more things, or the fact of their objective distinctness.

A Super-Humean cannot appeal to the intrinsic properties of particles to distinguish them, since Super-Humeanism admits only ontic structure within its supervenience base. However, its supervenience base is extremely sparse, since the only perfectly natural constituents it admits are distance relations. Super-Humeanism thus depends upon the following form of the principle of the identity of indiscernibles:

*Super-Humean principle of the identity of indiscernibles*
SPII: If object $O_1$ stands in a distance relation to some object $O_i$ if and only if object $O_2$ does too, then $O_1$ is identical to $O_2$.

However, this principle leads to implausible results, which come at a theoretical cost. This objection can be made more forcefully by means of the following argument:

*Symmetric worlds argument:*

i. Suppose there are three non-identical particles, 1, 2 and 3, separated by distances $d_{12}$, $d_{13}$ and $d_{23}$, and suppose they trace a locus such that $d_{12} = d_{23}$.

ii. If Super-Humeanism is true, then particle 1 is identical to the relations $\{d_{12}, d_{13}\}$, and particle 3 is also identical to the relation $\{d_{12}, d_{13}\}$.

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iii. Therefore, Super-Humeanism implies that particle 1 is identical to particle 3 (by ii).

iv. Therefore, Super-Humeanism is false (by i & iii).

The second premise is simply a restatement of that form of the principle of the indiscernibility of identicals to which Super-Humeans are unavoidably committed (SPII). The argument hangs, then, by the first premise, which may be rephrased as the modal claim that it is possible for there to be two non-identical particles that stand in the same distance relations.

I make this claim on the basis that we can *conceive* possible scenarios in which there are two particles that stand in the same distance relations. In fact, we frequently do so in considering textbook examples, such as the cases of spatially homogeneous and isotropic cosmological models, in which all of the particles, by the above reasoning, would be identical to each other [Wüthrich, 2009]. The relevance of this claim to my argument depends upon the commonly held assumption that the conceivability of some state of affairs offers evidence for its possibility, albeit only a defeasible kind of evidence.

The evidence required for the first premise is easy to come by. For example, consider a world in which particles 1 and 3 are making a circular orbit of the same radius around particle 2. In such a world, the distance between particles 1 and 2 is identical to the distance between particles 2 and 3, hence $d_{12} = d_{23}$. Whilst this scenario is perfectly conceivable, and such a system can be modelled straightforwardly using quantum mechanics, Super-Humeanism entails that there is *no possible world* in which it could ever be realised. It cannot be realised because the supervenience base in a Super-Humean world is *too sparse* to individuate particles 1 and 3. This counts as evidence for the first premise, in support of the conclusion that Super-Humeanism is false.

Such scenarios are commonly referred to as ‘Max Black’ worlds, which are possible worlds that contain indiscernible objects that we have reason nonetheless to consider distinct [Black, 1952]. In Max Black’s original example, we are asked to imagine a world with two distinct but qualitatively indiscernible spheres that stand one mile apart. In fact, the number of Max Black worlds that can be offered in evidence against Super-Humeanism may be multiplied *ad infinitum* by conceiving any number of symmetric configurations of particles in which many of the particles stand in identical sets of distance relations.

### ii. *Strong and weak structuralism*

This generalisation of my argument against Super-Humeanism is analogous to John Hawthorne's criticisms of *causal structuralism* [Hawthorne, 2001], in which he distinguishes two forms of structuralism. According to the *strong form* (as I shall call it), two things are identical if they play identical roles in a structure, where the roles that they play are defined abstractly without reference to the identities of things in the structure. According to the *weak form*, the roles that they play are defined concretely in terms of relations to relata whose identities are independent of their roles. Hawthorne's criticisms are directed toward the strong form of causal structuralism, in which a natural property is supposed to have an individual essence consisting of nothing over and above its 'causal profile'. This view is troubled by intra-world duplications of causal profiles resulting from the possibility of symmetric structures. However, Hawthorne notes that a weak form of causal structuralism can be defined that avoids this trouble, in which the necessary and sufficient conditions for being a particular property are specified in terms of its relations to other properties, whilst properties have identities independently of their causal roles. For the weak form to be viable, a property must have a *quiddity* over and above its causal profile.

Similarly, Super-Humeanism advances a strong form of structuralism, in which a particle has an individual essence consisting of nothing over and above its 'distance profile' (so to speak). This view is troubled by intra-world duplications of distance profiles resulting from the possibility of symmetric configurations. A weak form of structuralism, in this case, would be one in which the matter points have identities over and above the structure of distance relations they instantiate. For this view to be viable, each particle would require an *haecceity* that exists over and above its distance profile.

This parallel move, however, is unavailable to Super-Humeans, since it would require the abandonment of ontic structural realism. If the featureless particles of Bohmian mechanics have an *identity* over and above their distance relations, they cannot be *constituted* solely by distance relations. If each of the matter points which instantiate these relations has an haecceity, this configuration is not an ontic structure (cf. OS2). Yet if the Bohmian particles are constituted neither by properties nor relations, and they have no haecceities over and above the distance relations in which they stand, it is unclear how they are supposed to exist as distinct objects. (I shall pursue a weak structuralist model in Chapter 5.)

### iii. *Weak discernibility*

As an alternative strategy, we might consider appealing to the 'weak discernibility' of particles in symmetric configurations. Two objects may be said to be *weakly discernible* if they stand in some irreflexive relation [Quine, 1976]. Simon Saunders has argued that, whilst we should retain the principle of identity of indiscernibles, it is sufficient that physical particles should be weakly discernible in order for them to count as distinct objects [Saunders, 2003, Saunders, 2006]. A distance relation is an example of such a relation: the two spheres in Max Black's original example, for instance, are weakly discernible, since each object is one mile from the other, but is not one mile from itself. The examples used by Saunders to illustrate his claim are drawn from quantum mechanics: two particles in the singlet state may be considered weakly discernible, insofar as each particle 'spins' in the opposite direction to the other, but not in the opposite direction to itself. These particles are fermions, which are anti-correlated with respect to their spin. Yet there are also quantum-entangled states involving bosons, which are positively correlated with respect to their spin. These particles are not weakly discernible.

However, Katherine Hawley has argued that the claim that objects are distinct just in case they are weakly discernible is unmotivated [Hawley, 2006]. Noting that Saunders is effectively using (PII) to settle the 'inverse special composition question' and decide when quantum-entangled systems may be considered to have basic constituents, Hawley observes that an appeal to weak discernibility is merely an appeal to the fact that positing basic constituents is not *forbidden* by (PII). To argue that we should actually posit basic constituents in such cases is to invoke a supplementary principle: namely, that we should posit the existence of basic constituents whenever this is not forbidden by (PII).

Hawley offers three objections to adopting this supplementary principle. First, in the case of the property of spin, it seems arbitrary to regard the relation of being-of-the-opposite-spin as a 'better or worse claim to ontological basicness' than the relation of being-of-the-same-spin. On such a basis, Saunders claims that fermions are distinct objects but bosons are not. Secondly, the supplementary principle leads to arbitrary divisions within physical systems. For example, a system with four units of charge, according to this principle, could be partitioned into two basic constituents, where the first has a single unit of charge, and the second has three units. Thirdly, maintaining both (PII) and the supplementary principle involves holding conflicting motivations: (PII) favours mereological simplicity over complexity, by restricting our ontology to the minimum requirements of Leibniz's law, whereas the supplementary principle prefers mereological complexity over simplicity, whenever we can get away with it.

Perhaps that is not quite right. Saunders' proposal – with its conflicting motivations – might make sense as an account of the individuation of substances, if Leibniz's law were properly restricted to integral parts. In that case, the realisation of Saunders' principle, in a Super-Humean world, would require the reification of the nodes in the structure of distance relations, in order to avoid the problem of symmetric worlds and the collapse of the cosmic substance into its integral parts. Such a move would amount to postulating a substrate of bare particulars with haecceities that are somehow united with a spatial structure – which may sometimes be symmetric

– to compose a single substance. (I shall take up this thought again in Chapter 6). Once again, however, the particles would require *haecceities*, and Super-Humeans would have to abandon their commitment to ontic structural realism.

iv. *Symmetric worlds dilemma*

As I have noted, it is possible to avoid the problem of symmetric worlds whilst maintaining a weak form of Bohmian structuralism. On the one hand, although Leibniz's law requires us to recognise the non-identity of physical systems that instantiate incompatible properties, apparent heterogeneity might be taken to correspond to modifications of a single substance (as Hawley notes). On the other hand, since Leibniz's law is logically independent of (PII), one might favour a model in which particles with distance relations are posited as putative elements. Either move, however, would amount to admitting the existence of haecceities and abandoning the strong form of structuralism. Super-Humeans are thus confronted with a dilemma:

> *The symmetric worlds dilemma*
> Either (i) posit particles with haecceities, or (ii) deny the possibility of symmetric configurations.

Since Super-Humeans cannot appeal to particles with haecceities without rejecting ontic structural realism, they must take the second horn of the dilemma and deny that symmetric configurations of particles could exist in any possible world. They must maintain this posture in spite of the fact that the dynamical equations of physical theories admit symmetrical solutions, and the particles comprising a Super-Humean world would have an eternity in which to explore their configuration space. This prohibition must extend to solutions in which the configuration of particles is momentarily symmetric at certain times, or risk affirming the bizarre possibility of a 'peekaboo' cosmos whose particle configuration vanishes at certain times.

The symmetric worlds problem for Super-Humeanism has its roots in what Jukka Keränen introduced as 'the identity problem' in the philosophy of mathematics [Keränen, 2001]. On the one hand, symmetries are supposed to be a guide to the ontic structures, insofar as it is the structures of two rival theories with different ideologies but isomorphic structures that are taken to be ontic by structural realists. Such theories are acknowledged to be true by structural realists only up to an isomorphism. On the other hand, the ontic structures are also supposed to individuate the objects in the ontology, insofar as ontic structuralists are not eliminativists about objects. For Super-Humeans, the ontic structure consists solely of distance relations, and the objects are the particles referred to by Bohmian mechanics. However, as Keränen points out, such structures cannot *both* be symmetrical *and* individuating.

Esfeld is aware that symmetric configurations present a difficulty for his metaphysical model, but thinks Super-Humeans should bite the bullet and deny that symmetries are a guide to the ontic structures. This stance may be supported by two claims. First, Super-Humeans might claim to be only in the business of describing the actual world. Secondly, Super-Humeans might simply deny that symmetric configurations of its particles are in fact conceivable.

With respect to the first move, Super-Humeans might seek to justify the exclusion of entirely symmetric worlds by observing that the actual world is obviously not symmetrical (at least, as far as we can tell), and by pointing out that all physical theories have surplus mathematical structure [Esfeld and Deckert, 2017, p.69]. For example, the solution to the Klein-Gordon equation is the difference between a 'retarded' and an 'advanced' Green's function, but the advanced Green's function is typically discarded for problems involving time. According to Super-Humeans, we should likewise regard symmetric solutions to the dynamical equations of physical theories as 'mathematical surplus', which have no bearing on what the world is like.

Nonetheless, the rejection of a solution to an equation of motion usually concurs with our modal intuitions, whilst many physicists concur in finding symmetric solutions to be possible. For example, cosmologists who have contemplated the famous Friedmann-Lematre-Robertson-Walker solutions to Einstein's field equations, which describe homogeneous and isotropic spacetimes, have apparently considered them possible (concerning problems with spacetime structuralism, see [Wüthrich, 2009]). Moreover, in effectively banning symmetric configurations from the past or future, the Super-Humean is not merely describing the world as we find it – "Just the facts, ma'am", like any law-abiding Humean – but prescribing how particles should behave in all possible worlds with the same laws. Ironically, in seeking to produce an account of nature that is more Humean than neo-Humeanism, Esfeld has committed himself to a strong modal claim.

A committed Super-Humean, then, is likely to challenge the uniformity of the evidence of our modal intuitions. Whereas philosophers like Wüthrich may take the metaphysical possibility of symmetrical configurations for granted, Super-Humeans may claim to be unable to conceive perfectly symmetric configurations, along with philosophers like Hacking and Belot [Hacking, 1975, Belot, 2001]. More precisely, such philosophers claim that we have no reason to think that this is the correct description of what it is that we imagine, when we suppose ourselves to be imagining symmetric worlds. Super-Humeans will thus maintain that there is no possible world that must be described in a way that is incompatible with (PII).

Nonetheless, the Super-Humean refusal to take symmetry as a guide to the ontic structures comes at the cost of isolating their primitive ontology from any input from the empirical sciences, leaving Super-Humeans with ontological parsimony or simplicity as their only metaphysical guide. This is the cause of Lazarovici's complaint that Super-Humeanism is a 'one-trick pony' [Lazarovici, 2018], since the determined Super-Humean will only argue that, if the criterion of ontological simplicity is properly elevated, it will uniquely favour their primitive ontology. In what follows, I offer reasons for thinking the pony stumbles in performing its only trick.

## §4.4. A TEMPORAL DILEMMA

My second objection calls into question whether Super-Humeanism can offer a realist account of the laws of nature, given its structuralist conception of matter and its notion of primitive change. I shall argue that these two commitments lead to a dilemma between two contrary views of time: namely, a presentist view, in which only one configuration exists at a particular moment of time, and an eternalist view, in which every configuration exists for all time.

### i. *In favour of presentism*

On the one hand, Super-Humeans require that particle configurations should change for the sake of empirical adequacy. Yet they cannot appeal to the so-called At-At theory of change advanced by Bertrand Russell [Russell, 1903, pp.469-473],[7] in its ordinary form, in which individuals change by instantiating different properties at different times, because they reject the assumption that the particles are primitively individuated by their physical properties. Rather, Super-Humeans embrace a structuralist conception of the particles, in which they lack any intrinsic physical properties, but are holistically individuated by the distance relations in which they stand. Likewise, Super-Humeans cannot embed the particle configurations as points within a primitive spacetime, because they adopt a Leibnizian conception of space, in which space is also constituted by distance relations.

Nor is it sufficient for Super-Humeans to adopt as real an eternal series of configurations, minus the usual background conception of spacetime, without explaining how the time-slices comprising this series are supposed to be individuated as temporal parts of a single structure. At first glance, it seems they might introduce primitive temporal relations between each of the particles. Yet it is unclear how such particles might be supposed to instantiate two qualitatively distinct kinds of relations without abandoning minimalism. Super-Humeans are committed to a strong form of structuralism, in which all of the matter points at a moment of time must be holistically individuated by the *intra*-structural relations that constitute a particular configuration, because they lack any intrinsic properties or primitive identities. Since these configurations also lack intrinsic properties, over and above their constituents, it seems that they would also have to be holistically individuated in terms of distance relations, in order to instantiate *inter*-structural relations across time-slices within an eternal stack of configurations.

However, as Lazarovici points out, the distance relations that constitute both the particle configurations and the physical space in which they move are directionless, structureless and dimensionless [Lazarovici, 2018].[8] In that case, it is difficult to see how Super-Humeans who adopt an eternal stack of configurations can explain the structure of time. For instance, a scientist who sets up a measuring apparatus to measure the positions of particles, *before* measuring their positions, then makes the measurement, *before* writing the result down, does not set up the apparatus *after* writing the result down, nor make the measurement *before* setting up the apparatus. Yet why should the temporal order be both transitive and anti-symmetric in a world made solely of distance relations? It is also difficult to see how Super-Humeans can explain the difference between primitive change in the configuration of the particles, and a variation in their distribution along some dimension, without appealing to additional brute matters of fact.

In short, in order to get these Bohmian particles to change their configuration, it seems Super-Humeans will have to 'clear the deck', so to speak, of one set of distance relations, before replacing it with another. This suggests Super-Humeans should adopt a presentist view of time, in which there is only one configuration of particles that exists at the present moment. (This appears to be Esfeld's position.)[9]

ii. *In favour of eternalism*

On the other hand, Super-Humeans require the existence of an adequate supervenience base for the wave function, which must include facts about potential configurations for all of time. In Esfeld's view, this base is composed of an infinite number of time-slices, in which each time-slice consists of an arrangement of matter points. He requires the existence of such an extensive base because a law that includes the wave function does not supervene upon, and is not wholly made true by, the distribution of particles at a particular time.

Of course, all Humeans who toy with presentism will face the problem of finding truth-makers for propositions about entities that do not supervene upon what exists at the present moment, such as universal laws of nature. However, there is an additional complication for Super-Humeans seeking to accommodate quantum phenomena. To bring out this difference, consider how the laws are represented in a classical world, according to neo-Humeans, and in a quantum world, according to Super-Humeans. In a classical world, one configuration of properties $P_i$ follows regularly from another $P_j$ according to a law $L : P_i \rightarrow P_j$ that refers to distinct configurations of properties instantiated in the world at different times. However, in a quantum world, a best systems account of the world will include only positions and a wave function, $L : (Q_i, \psi_i) \rightarrow (Q_j, \psi_j)$, whilst Super-Humeans will insist there is nothing besides matter points which may serve as referents.

Yet matter points are constituted by nothing but distance relations: they have no intrinsic physical properties, since any properties are on the same level as the wave function, which is merely part of the 'best system' account of how these matter points are distributed for all time. It follows that the truth of any propositions that pick out objects by their physical properties, including microscopic objects such as electrons with properties like mass and charge, will fail to supervene upon what exists at the present moment, or upon any local matters of fact, but will depend for their truth upon nothing less than the whole stack of configurations for all time.

In short, in order to secure a supervenience base of a wave function conceived as a nomological entity, and in order to save their commitment to scientific realism, it seems Super-Humeans will have to 'join the dots', so to speak, by uniting each particle configuration as temporal parts of a single structure. This suggests Super-Humeans should adopt an eternalist view of time, in which the cosmos is comprised of a series of time-slices, where every slice is as real as the series of which it is part.

### iii. *Temporal dilemma*

If Super-Humeanism entails both presentism and eternalism, however, it contains a flagrant contradiction. Super-Humeans are thus caught on the horns of a dilemma:

> *Temporal dilemma*
> Either (i) embrace presentism, but abandon scientific realism, or (ii) embrace eternalism, but abandon strong structuralism.

To take the first horn of the dilemma, by embracing presentism, would be to abandon the truth of a law of nature that includes the wave function, as well as the truth of propositions that refer to the physical objects that scientists interact with in their experiments. Might this consequence be averted?

On the one hand, Super-Humeans could attempt to compress the facts upon which they depend within a single time-slice, by making facts about future time-slices depend upon facts about a past time-slice. One configuration might be supposed to necessitate another. (I explore this possibility in Chapter 5.) However, according to Super-Humeans, there are no necessary connections between any of the time-slices. On the other hand, Super-Humeans might attempt to soften the requirements of realism, by claiming that the truth of the laws of nature could be fixed at the end of the world (that is, a future time-slice). Super-Humeanism might then be reconciled with presentism by appealing to memory: just as the present configuration of particles may be supposed to contain the memory of past changes, so the eschaton may be supposed to contain the memory of every past change.

Yet it is difficult to see how memory could play a role in grounding the truth of any laws without endowing memories with the kind of necessary connections that all Humeans reject. Whether or not mnemonic impressions qualify as memories is surely something that is consequent upon the laws of nature, whereas Super-Humeans who appealed to memory to ground the truth of these laws would have to appeal to additional facts, over and above the positions of the particles, which would have to be correlated somehow with their positions in past time-slices.

In any case, I doubt that the eschaton holds any hope in store for Super-Humeans, however long their memories. Suppose they take the eschaton literally. In that case, they would have to believe that some future time-slice $t_f$ will instantiate a primitive property of 'finality', such that the primitive arrow of change will not point to a future time-slice at time $t = t_f$. However, such a move is unavailable to Super-Humeans who embrace a strong form of structuralism: by stipulation, there are no primitive or intrinsic properties in nature. Suppose they take the eschaton metaphorically instead. In that case, they would have to deny that there is some time-slice that is identical to the end of the world. If so, any law that depends for its truth upon the eschaton could not literally be true, and Super-Humeans could not be realists about laws.

To take the second horn of this dilemma, by embracing eternalism, would be to abandon the minimalism of Super-Humeanism, in which both the space in which particles move, and the particles that move through space, are constituted by distance relations. Yet there is more than one way of being an eternalist, according to whether one adopts the 'A-theory of time', which posits an absolute distinction between past, present, and future, or the 'B-theory', which denies the existence of such a distinction [McTaggart, 1908]. Perhaps we can find a compromise.

On the one hand, Super-Humeans attracted to the B-theory of time might form an eternal series of configurations by embracing a substantival conception of spacetime.[10] In doing so, however, they would introduce a difficulty concerning how the distance relations that constitute the particle configuration are to be embedded in spacetime without abandoning their structuralist characterisation of matter. In abandoning either the Leibnizian conception of space, or the strong form of structuralism, they would have to abandon Super-Humean minimalism, which claims that its world-making relations are sufficient for constituting a world of physical objects.

On the other hand, Super-Humeans attracted to the A-theory of time might attempt to construct an eternal series of configurations by adopting the so-called 'moving spotlight theory'.[11] In this case, we might think of the world as consisting eternally of a block of facts about distance relations in different time-slices, whilst requiring the existence of 'presentness' as a property of a time-slice, along with the properties of 'pastness' and 'futurity'. Primitive change in a block-universe may then be understood in terms of the instantiation of these properties. However, setting aside the problems that have been raised with the moving spotlight theory (for examples, see [Sider, 2001, 2.1]), such a move also violates Super-Humean minimalism: by stipulation, there are no primitive or intrinsic properties in nature.

Perhaps we can split the temporal dilemma. In the Growing Block theory of time, advanced by Michael Tooley [Tooley, 2000], the past and the present both exist, but the future does not. Yet surely this represents the worst of both possible worlds for Super-Humeans. On the one hand, like the presentist view, it fails to offer an adequate supervenience base for laws and physical properties, since the future does not exist yet. On the other hand, like the spotlight theory of time, it requires the existence of 'presentness' as a property of a time-slice, along with the properties of 'pastness' and 'futurity'. It seems, then, that Super-Humeans are caught on the horns of the temporal dilemma. To take either horn would be to undermine the Super-Humean account of the truth of the Bohmian law, either by abandoning its minimalism, or by abandoning its realist stance toward laws.

## §4.5. Problems for persistence

My third objection concerns whether Super-Humeanism can offer an ontology of particles, given its structuralist conception of matter and Leibnizian conception of space. Specifically, I am concerned with a question raised by Lazarovici: what provides for the identity of the matter points over time? [Lazarovici, 2018, p.82].

### i. *From matter points to spaghetti*

Clearly, a world made of matter points need not be a world that contains *particles*, which persist through time; it might contain *flashes*, which appear discontinuously throughout space. Since matter points are constituted by distance relations, we cannot appeal to their enduring properties in specifying their persistence conditions. Since matter points have no temporal parts that are instantiated in spacetime, we cannot appeal to their perdurance. The persistence conditions for an ontology of particles, in a world of matter points and primitive change, must be cashed out at the level of the ontic structure.

However, it is impossible to formulate persistence conditions for particles in terms of the persistence of the elements of this structure, since a set of distance relations has no identity over and above its members, such that it can survive a change in its membership. A world in which distance relations primitively change is a world in which one set of ontic relations come into being (or 'presentness') followed by another, where each set has a different identity from the previous set. Since there are no substances which instantiate these ontic relations, nor any primitive spacetime in which they are embedded, there is nothing to unite these sets of relations as a persisting subject of change.

A more promising solution might be to attempt to formulate persistence conditions for the particles in terms of the *trajectories* traced by the matter points instead. In a Super-Humean world, it is a brute fact that the number of matter points in this world is fixed, and the distance relations between them are non-vanishing. Suppose that primitive change were discrete, such that, in the temporal interval $(t_1, t_2)$ , where $t_2 > t_1$, there were only a finite number of numerically distinct time slices. In that case, it would be a world of flashes rather than particles, in which different matter points would appear at certain points along each Bohmian trajectory. However, suppose primitive change in this world were continuous, such that, in the temporal interval $(t_1, t_2)$, there were an actually infinite number of time-slices. In that case, matter points would *prima facie* trace continuous trajectories that do not cross. We might think of Bohmian particles, then, as persisting by enduring.

However, I have doubts about the coherence of conjuring the identities of particles from their trajectories. To begin with, a set of trajectories need not represent continuous motion. Consider a world $W_1$, in which there are three particles that follow continuous trajectories, and a second world $W_2$ containing three particles whose trajectories result from splicing the second half of particle 1's trajectory in $W_1$ to the first half of particle 2's, and the second half of particle 2's trajectory to the first half of particle 1's, whilst the motion of particle 3 is left unchanged. $W_2$ is a world in which particle 1 hops to the site of particle 2, just as particle 2 hops to the site of particle 1. The trajectories in $W_2$ are identical to those in $W_1$. Nonetheless, they represent discontinuous motion.

To eliminate the possibility that trajectories might represent discontinuous rather than continuous motion, Super-Humeans will have to rule out the possibility of worlds like $W_2$, even though $W_2$ is empirically indistinguishable from $W_1$. In this respect, the Super-Humean is in the same boat as the weak structuralist who introduces haecceities, which are not empirically discernible, to secure the identities of the particles. In that case, the particles would not be matter points, but matter spaghetti, in which the essence of each particle is cashed out in terms of a densely ordered set of sets of distance relations.

### ii. *Uncoordinated matter spaghetti*

Replacing matter points with matter spaghetii, however, raises another difficulty: namely, the problem of how distinct strands of matter spaghetti compose a single configuration. In order for two or more strands to constitute a configuration of Bohmian particles that trace continuous trajectories together through space, we must find a way of coordinating simultaneity relations between the distinct sets of distance relations that belong to their different trajectories.

To tease out this difficulty, consider the case of a world of two particles, $A$ and $B$, in which particle $A$ traverses a trajectory between two distinct points in space, $(x_1, x_2)$, and particle $B$ traverses a trajectory between two different points, $(x_3, x_4)$. In a Super-Humean world in which change is continuous, the essence of a strand of matter spaghetti must be supposed to be dense in the spatial positions that constitute a trajectory. Yet why should we suppose that the ordering of positions in the interval $(x_1, x_2)$, for one strand of spaghetti, should correspond to the ordering of the positions in $(x_3, x_4)$, in another strand, in such a way that, for every infinitesimal increment $\delta x$ in the position of $A$ along its trajectory with each infinitesimal increment in time $\delta t$, there is a corresponding infinitesimal increment in the position of $B$? The two strands might be coordinated in such a way that, as particle $A$ advances from the spatiotemporal point $(x_1, t)$ to $(x_1 + \delta x, t + \delta t)$, particle $B$ jumps discontinuously in space from one point to another; for example, from $(x_3, t)$ to $(x_4, t + \delta t)$, where $|x_4| >> |x_3|$. In fact, there are an infinite number of ways of pairing points in $(x_1, x_2)$ with points in $(x_3, x_4)$, and hence infinitely many more ways of making a world of flashes rather than particles.

Or again, consider the possibility of a cyclic cosmos, of the kind contemplated in the 1920s by Einstein, in which the universe endlessly repeats the same process of expansion and contraction, which takes place in a period $T$. Suppose $Q_t$ represents the configuration of particles at some moment $t$. In that case, $Q_t$ will be identical to the configuration after $n$ periods, $Q_t = Q_{(t+nT)}$, where $n$ is any positive integer. It follows that any matter point in a strand of matter spaghetti $A$ that is coordinated with a matter point in a non-identical strand $B$ can be coordinated with an infinite number of matter points in $B$, and likewise with an infinite number of matter points in every strand of matter spaghetti. Why suppose, then, that the matter points in $Q_t$ instantiate a real relation of simultaneity? Indeed, why suppose that different strands of matter spaghetti compose a single particle configuration at all, such that every member of each strand must be paired with a member in every other strand and co-ordinated in time?

At this point, Super-Humeans may appeal to presentism, in order to impose a preferred ordering upon all of the matter spaghetti and unite them within a single evolving configuration. However, as I have suggested, this move comes at a theoretical cost: a Super-Humean world in which only one configuration of matter points exists at the present moment is a world in which the laws of nature and propositions referring to objects that scientists interact with in their experiments are left without truthmakers. The only alternative for Super-Humeans who appeal to matter spaghetti is to pile on additional brute facts: it must be a brute fact that all of the matter spaghetti composes a single configuration, and it must be a brute fact that matter points pair up in such a way that they constitute a world of particles that travel together through space. It seems Super-Humeans will have to help themselves to a great many brute facts to build a world of $10^{86}$ particles.

### iii. *Persistence dilemma*

I conclude that there is small hope of Super-Humeans deriving the identities of particles from their trajectories. Those who attempt to wrest themselves from the horns of the temporal dilemma concerning the nature of time will thus find themselves caught on the horns of a persistence dilemma concerning the nature of space:

*Persistence dilemma*

Either (i) abandon Leibnizian space, and embrace the At-At theory of change, or (ii) retain primitive change, but embrace particles with haecceities.

By seizing the first horn of this dilemma, we might explain how there are particles that persist, but must abandon any primitive notion of change: a particle that persists is one that perdures by tracing a worldline in spacetime, whilst any change in a physical system is to be explained by the instantiation of properties at different points in spacetime. However, Super-Humeans who take this option must give up both their ontological minimalism and their primitive notion of change. How should the distance relations that constitute the matter points be embedded in spacetime?

By seizing the second horn of the dilemma, we can explain how there are particles which persist without abandoning a primitive notion of change: a particle may persist by enduring if it has an haecceity that exists over and above the distance relations in which it stands. However, Super-Humeans who adopt this position must abandon their strong form of structuralism. How, then, should they understand a particle's capacity to change the distance relations in which it stands?

Thus to take either horn of the persistence dilemma would be to undermine the Super-Humean ontology of moving particles, either by abandoning its notion of primitive change, or by abandoning its conception of matter. It seems Esfeld's only recourse is to abandon minimalism by endowing particles with haecceities or by adopting a substantival conception of spacetime. (I shall consider a model in which the particles have haecceities in Chapter 5.)

## §4.6. General remarks

In this chapter, I have considered the Super-Humean metaphysics proposed by Esfeld. According to Esfeld, the world of macroscopic objects, such as our measuring devices, is composed of microscopic particles, which are distributed according to a law of nature specified by Bohmian mechanics. This law explains the 'non-local' measurement outcomes associated with quantum experiments, such as the famous EPR experiment, which involves two quantum-entangled particles.

Super-Humeanism offers a supervenience base for this law consisting of a changing configuration of matter points, which have no intrinsic physical properties or powers, but are constituted solely by the distance relations in which they stand (Section 4.2). Super-Humeans thus depart from a 'classical' micro-monist conception of reality, in which the physical world is built up of basic constituents with intrinsic microphysical properties (MM/I), and abandons the neo-Humean mosaic of sparse natural properties in favour of distance relations. According to this alternative picture of nature, we should think of the cosmos as an integral whole, rather than a mereological sum, which has particles as its integral parts.

However, I have argued that Super-Humean minimalism comes at a theoretical cost and introduces conceptual problems. First, I argued that its conception of matter fails to discern between any number of Max Black worlds that contain symmetric particle configurations (Section 4.3). Super-Humeanism is thus saddled with the implausible modal claim that a Bohmian particle configuration is necessarily asymmetric. Secondly, I argued that its account of the truthfulness of the Bohmian law of motion leads to a self-undermining dilemma concerning the nature of time (Section 4.4). For this law to be true, the particle configurations would have to support necessary connections. Finally, I argued that the Super-Humean account of the endurance of particles leads to a self-undermining dilemma concerning the nature of space (Section 4.5). For particles to persist, they must have some intrinsic identity, over and above the distance relations in which they stand.

In short, it seems that the problems with Super-Humeanism can only be solved by taking the following two steps: first, rejecting the minimalism imposed by its strong form of structuralism, in order to secure physical objects that persist through time; secondly, lifting its Humean embargo of necessary connections, in order to secure an adequate supervenience base for its laws. In the light of this discussion, I suggest the following desideratum to guide the construction of a more adequate ontology:

*Desideratum: Objects with causal powers and intrinsic identities*
DD/II: Other things being equal, we should favour metaphysical accounts in which the objects of scientific inquiry have causal powers and intrinsic identities, over and above the relations in which they stand.

In what follows, I will suggest a number of alternatives to replace Super-Humeanism, which embody this desideratum by adopting an ontology of powers. Whilst Esfeld admonishes philosophers against the 'illusion' of supposing that, by enriching our primitive ontology beyond matter points, we can expect to achieve explanations that are any 'deeper' than those offered by Super-Humeans [p.7], it seems that Super-Humeans do not, after all, have superpowers for deflecting metaphysical trouble. This being the case, I suggest that metaphysicians and philosophers of science should balance Esfeld's injunction in favour of minimalism against some advice attributed to Einstein: namely, our models should be as simple as possible, but not any simpler.

## Notes

[1]Esfeld uses only two axioms, (SH1) and (SH3). I have modified the wording of the axioms slightly, for convenience, and added (SH2) to incorporate his views on grounding and substances.

[2]Thus avoiding some of the objections commonly raised against more radical forms of ontic structural realism (eg. [Briceño and Mumford, 2016]), such as the version espoused by Ladyman and French in [French and Ladyman, 2003]. For further discussion, see [Esfeld, 2019].

[3]The positions of a particle configuration defined in a Minkowskian spacetime would not be observer-independent.

[4]See [Ramsey, 1978]; [Lewis, 1973], pp. 73-75, [Lewis, 1987] (postscript) and [Mill, 1875] (Book III Chapter IV).

[5]In refining my objections, I have benefited from correspondence with Esfeld and Koons.

[6]Parts of this section, and the following two sections, draw upon my recent publication [Simpson, 2019], and some sentences are taken verbatim.

[7]Christened by Peter Geach as 'mere Cambridge changes' [Geach, 1969].

[8]Lazarovici focusses on how space is 'lost' by reducing all geometric structure to distance relations: 'There is nothing about the distance relations that would make them 3-dimensional or put any other constraints on the dimension, curvature or topology of the physical geometry' [Lazarovici, 2018, p.82].

[9]See [Esfeld and Deckert, 2017, pp. 151-152]: '...change exists, but not a whole ordered stack of configurations Presentism, thus conceived, is the most simple and parsimonious ontology, since only one configuration exists.' However, Esfeld does not adopt a primitive arrow of time.

[10]John McTaggart claimed there can be no real or primitive change in the block-universe conceived in the B-theory of time [McTaggart, 1908], although many philosophers disagree with him.

[11]The basic idea is found in [Broad, 1923, pp.59-60], although Broad does not assert this theory.

Chapter 5

# A network of power-atoms

*I shall be telling this with a sigh... Two roads diverged in a wood, and I - I took the one less traveled by.*

– Robert Frost, *The Road Not Taken*

## §5.1. Powers and structure

In the previous chapter, I considered the metaphysics of Super-Humeanism, which provides a supervenience base for the laws of Bohmian mechanics, and affords an ontology of nature that maintains certain standard assumptions of scientific inquiry (AI/I-III). I advanced a number of arguments against Super-Humeanism, in the form of a symmetric worlds problem (Section 4.3), a temporal dilemma (Section 4.4), and a persistence dilemma (Section 4.5), which challenge its conception of matter. At the heart of these problems is the *strong* form of structuralism espoused by Super-Humeans, in which the Bohmian particles are 'matter points' that have no identities over and above the distance relations in which they stand, combined with the Humean embargo of necessary connections, which prevents one particle configuration causing or necessitating another.

In this chapter, I shall propose an alternative ontology for the Bohmian interpretation of quantum mechanics, for the purpose of addressing all three of these problems. I mean to do so by adopting a *weak* form of structuralism, and by endowing the Bohmian particles with causal powers. An ontology of powers can account for natural phenomena, like the motion of microscopic particles, by providing a conceptual framework that reconciles persistence with primitive change. First, a powerist might conceive change as the actualisation of a potentiality that is intrinsic to the subject of change. It is in exercising its powers that a subject brings about change, whilst remaining essentially unchanged. Secondly, powerists do not need to posit a primitive arrow of change, over and above the things that are changed, because a power to bring about change exhibits what Molnar called 'physical intentionality', being directed toward future actualities [Molnar, 2006, pp. 60-81]. For powerists, the passage of time involves intrinsic changes that actualise prior potentialities.

My aim in this chapter is to construct and explore a half-way house between Humeanism and Aristotelianism, by offering a metaphysics of physics which adopts a Humean conception of laws, but deploys causal powers to bring about necessary change. In so doing, I shall be implementing Heather Demarest's proposal of taking a 'best-systems' approach that is 'anti-Humean in its ontology, but Humean in its laws' [Demarest, 2017], and following Mauricio Suarez' suggestion of accounting for entanglement in terms of the 'Bohmian dispositions' of particles [Suárez, 2015]. Whereas the Super-Humean strategy combined the primitive ontology approach to quantum mechanics with Ladyman's account of ontic structural realism [Ladyman and Ross, 2007], I propose to combine the primitive ontology approach with a modified version of Marmodoro's account of power structuralism [Marmodoro, 2018a].

## §5.2. Local power-atoms

The core of this model – the first of three metaphysical models that I shall propose in this thesis – may be laid out in two axioms:[1]

*Bohmian power structuralism*

PM1: There are power-atoms, which exercise causal powers to change their velocities in response to their spatial configuration.

PM2: The power-atoms are the substrate of all physical change; it is the distance relations between them that change.

The primitive ontology, in this case, consists of elements I shall call power-atoms, rather than matter points.[2] This model is called *Bohmian power structuralism*, which modifies the Super-Humean model in various ways.

### i. *Matter*

For the power structuralist, physical systems are composed of power-atoms, and each power-atom exercises a power to change its velocity. However, the way in which a power-atom exercises its power ontologically depends upon the total configuration of power-atoms, which is explicated in terms of their distance relations. The power-atoms instantiate distance relations, because in exercising their powers to change their velocities, they change the distance relations in which they stand. The power-atoms instantiate relations of ontological dependence, because the velocity profile that they manifest at any given time $t$ depends upon the positions of all the power-atoms at time $t$ (that is, upon the total set of distance relations), and they must collectively 'co-manifest' their powers. In this model, the configuration of the power-atoms at time $t$ serves as a 'stimulus condition' for the velocity profile $v^{\psi}(t)$ specified by Bohmian mechanics. In order to implement this model, however, there are several issues that will need to be addressed.

The first issue I wish to clarify concerns the individuation of a power-atom within the configuration to which it belongs. Do power-atoms have their own intrinsic *identities*, or are they, like matter points, holistically individuated according to their 'position' in the total configuration? In order to avoid the problem of symmetric worlds (see Section 4.3), there must be more to the identity of a power-atom than the distance relations in which it stands. According to the *strong form* of structuralism adopted by Super-Humeans, two things are identical if they play identical roles in a structure, where the roles that they play are defined abstractly without reference to the identities of things in the structure. According to the *weak form*, by contrast, the roles that they play are defined concretely in terms of relations to relata whose identities are independent of their roles. I propose to adopt a weak form of structuralism in which each power-atom is attributed an *haecceity*.

Although more commonly found in medieval metaphysics – most famously, in the work of the medieval philosopher Duns Scotus – haecceities have also been deployed by some modern philosophers, like Kant and Peirce. I shall require a power-atom $i$ to have an haecceity $H_i$, which is a unique property that no other object possesses: namely, the property of being *this* particular power-atom. Such a property individuates the power-atom. More precisely:

$$\forall i \forall j \left( i = j \Leftrightarrow H_i = H_j \right). \tag{5.2.1}$$

Perhaps it is not strictly necessary to introduce haecceities in this model, in order to individuate the power-atoms. Nevertheless, it would require further metaphysical inquiry to avoid them, and so I shall tolerate them for the purpose of this discussion.

The second issue I wish to clarify concerns the relation between a power-atom and its power to move in physical space. Is a power-atom *identical* to its power, or does it simply *have* a power? Marmodoro has put forward an ontology in which there are 'power-tropes' that exist at the fundamental level of reality, which are instances of pure powerfulness [Marmodoro, 2018a]. She claims that properties like mass, spin and charge may be treated as power-tropes that compose different particles.

To say that power-atoms are power-tropes, however, would be to claim that there is nothing more to being a power-atom than the powers it exercises. Yet if power-atoms have haecceities and stand in distance relations, there is clearly more to being a power-atom than its powerfulness. In fact, a power-atom's power must be defined concretely in terms of the primitive identities of the power-atoms. It seems, then, that Bohmian power structuralists should say that power-atoms *have* powers.

The third issue concerns the *essence* of a power-atom. If a power-atom has a power, is that power an essential feature of the power-atom, or is it merely accidental? Suppose we assume that each power-atom $i \in (1, \ldots, N)$ in a configuration of $N$ particles with a wave function $\psi$ has a power to move with velocity $v_i^{\psi}(t)$ at time

$t$ in response to the current configuration $\{Q_1, ..., Q_N\}$, but that this power changes at each moment in time, whilst the power-atom remains unchanged. In that case, the power would be *accidental* to the power-atom. Unless we posit something in addition to the power-atoms, which has the power to change their powers (I consider such a model in Chapter 6), this change in the powers at each moment of time would be a brute change without further explanation. Furthermore, it would be entirely mysterious why the power-atoms should always acquire powers with holistic stimulus conditions that always co-manifest. Such a model comes at a high theoretical cost, and its explanatory virtues are doubtful.

Suppose that each power-atom has its power to move *essentially* instead. In that case, if a power-atom's power to move at velocity $v_i^\psi(t)$ were to change at time $t$, when the particle configuration changes, the power-atom would itself have to be replaced with a different power-atom, which has a different power to move at a velocity $v_i^\psi(t + \delta t)$. In that case, the whole configuration of power-atoms would have to change essentially at every moment in time. This model runs into serious difficulties. For one thing, such a change implies the creation *ex nihilo* of one particle configuration after another, which stretches credulity. For another, it cannot support a configuration of particles that persists through time.

Third time lucky. Suppose a power-atom has an essential power to move and persists through time, whilst the *manifestation* of its power changes from moment to moment. In that case, a power-atom must come equipped with a *multi-track* power (the term was coined in [Ryle, 1949]), in which the specific manifestation of its power depends on the particular way in which it is stimulated (see [Ellis and Lierse, 1994, Vetter, 2013] and [Bird, 2007, pp.21-4]). We might think of the essence of this multi-track power as being represented by a $3(N-1)$ dimensional space, in which each 'position' in this space corresponds to a particular configuration of the other $N-1$ Bohmian particles (and hence to a particular track), and the magnitude at that position specifies the velocity of the particle possessing that power (and hence a particular manifestation). There is no occasion to physicalise this configuration space; it is simply a way of representing the *potentiality* of each power-atom's power.

Let's enhance the primitive ontology, then, to include power-atoms with multi-track powers. Nonetheless, despite endowing the Bohmian particles with intrinsic powers, power structuralists reject the 'classical' micro-monist picture of nature by affirming the radical holism of Bohmian mechanics (see Chapter 3). This holism is reflected in this model in the fact that every power-atom depends upon the position of every other power-atom for its stimulus conditions and upon the co-manifestion of all their powers. In a power structuralist world, it would be impossible to add or subtract a power-atom without altering the *essence* of every power in the network.

Following Marmodoro's account of power structuralism [Marmodoro, 2018a], then, the power structuralist thinks of the powerful nature of each power-atom as being constituted by a structure of ontological dependencies, such that every power-atom is essentially related to all the other power-atoms and they necessarily co-manifest their powers in a certain way. However, Bohmian power structuralism modifies Marmodoro's original account in two significant respects.

First, the original proposal identifies the primitive elements in its ontology with physical properties, like mass and charge. In combining power structuralism with the primitive ontology approach to quantum mechanics, we must drop this identification: Bohmian particles are 'featureless', insofar as they do not have intrinsic physical properties that can be picked out by a physical theory. Secondly, Marmodoro's original proposal endorses pandispositionalism in claiming that there are only powers at the fundamental level in nature. Nonetheless, the Bohmian power structuralist requires power-atoms to stand in distance relations, which are categorical rather than dispositional features of nature, in order to explicate the notion of a particle configuration. The velocity profile $v^{\psi}(t)$ of the configuration is simply the rate at which the particles are changing their relative positions.

The image of nature assumed in [Marmodoro, 2018a] is an essentially 'classical' picture of the world, in the sense I discussed in Chapter 3, inasmuch as it conceives microscopic particles as fundamental objects with intrinsic physical properties. These particles are built from power-tropes, like mass and charge, and they can be combined (or transformed) into larger objects.[3] Marmodoro's model seeks to include quantum spin among the basic properties of particles. In doing so, however, it runs into the *problem of non-locality*, since properties like spin that admit quantum superpositions cannot be treated as intrinsic properties of localised particles without violating Bell's theorem (see Section 3.2). Since the best candidate for reconciling a fundamental particle ontology with quantum mechanics is the Bohmian interpretation, yet Bohmian particles do not have intrinsic properties like spin, this model will have to be modified to incorporate quantum phenomena. For the remainder of this discussion, I shall refer to my replacement model simply as *power structuralism*, and any comments that I make about power structuralism will henceforward refer to my model, rather than Marmodoro's.

### ii. *Substances and entities*

According to Super-Humeans, there is only one substance that objectively exists in nature, which may be said to have properties independently of any other object: that is, the cosmos itself, of which all the matter points are integral parts. In contrast, if one thinks of a substance as a property-bearer that must be distinguished from the properties that it bears, it seems that power-atoms are a kind of substance, since power-atoms have intrinsic causal powers (FS/IV). However, they are a peculiar kind of substance, since one power-atom can never be said to act upon another power-atom in isolation from any of the other power-atoms. Rather, it is the configuration as a whole that enters into causal relations with each power-atom at each moment of time. What, then, is the ontological status of this global configuration?

On the one hand, the total configuration of power-atoms cannot compose a fundamental substance, according to the 'neo-Aristotelian' lights guiding this discussion, since a substance is a metaphysical unity that cannot be composed of other substances (FS/V). On the other hand, the total collection of power-atoms possesses a degree of *unity* that is much stronger than any arbitrary collection of entities, such as a heap of sand. Let us say, then, that the power-atoms in this metaphysical model constitute a tightly *integrated collective*, but one which lacks the degree of metaphysical unity that is required to be a substance. Such forms of unity are not foreign to our experience of the world. There are examples of such collective unities in biology, for instance, that fall short of the unity of a substance [Oderberg, 2017].

iii. *Laws of nature*

In the primitive ontology approach to quantum mechanics, the matter composing the objects of scientific inquiry evolves according to a law of nature, and the wave function enters the account through the nomological role that it plays in the temporal development of the matter. According to Super-Humeans, the nomological role of the wave function can be spelled out in terms of a 'best systems' account of laws.

For the purposes of offering an alternative 'semi-Humean' metaphysical model, I shall adopt a modified or 'reformed' view of the Mill-Ramsey-Lewis view of lawhood: I shall regard the Schrödinger equation and the Bohmian law of motion as supervening upon and being wholly made true by a set of non-nomological facts, but will allow this set to include facts about *potential* distributions of particles that are irreducible to categorical matters of fact. In this respect, I shall be following Demarest's proposal of taking a 'best-systems' approach that is 'anti-Humean in its ontology, but Humean in its laws' [Demarest, 2017].

For Super-Humeans, the supervenience base is composed of an infinite number of time-slices, where each time-slice is constituted by a set of distance relations. It also incorporates, in addition, a primitive arrow of change, so that one time-slice follows another, in order to explain how the Bohmian configuration changes. Each time-slice is thus a distinct *temporal part* of the changing configuration of Bohmian particles, with its own separate identity. In order to fix the truth values of laws that depend upon the distribution of particles for all time, such as a Bohmian law that includes the wave function, the Super-Humean may be tempted to adopt some form of eternalism such that all of the configurations can be said to exist at all times, although this results in some serious conceptual problems (see Section 4.4).

However, power structuralists do not need to expand their supervenience base to include numerically distinct configurations for each moment of time. Since the power-atoms have intrinsic and essential multi-track powers, power structuralism introduces a horizontal dimension within its explanatory structure that explains how the *same* set of power-atoms, which persist from time $t$ to $t' > t$, can co-manifest in *different* ways at times $t$ and $t'$, when subject to different stimulation conditions. For the power structuralist, the supervenience base at *any time* includes facts about potential future configurations, as well as facts about the configuration at time $t$, because the power-atoms have multi-track powers. There is therefore no need to posit numerically distinct 'time-slices', or a primitive arrow of change, in addition to the power-atoms, since the actual configuration of power-atoms at time $t$ is intrinsically directed toward other potential configurations at time $t'$, and the ways in which the power-atoms are arranged in space are purely accidental to their existence.

The difference between these two ways of forming the supervenience base comes down to a difference between two distinct attitudes toward *potentiality*. A Humean world, by stipulation, is a world without necessary connections, in which the potential of one thing to bring about another must be an artifact of our description of it. A world that contains primitive powers, by contrast, is a world of irreducible potentiality, in which some things are properly described in terms of the manifestations they have the potential to bring about under certain conditions.

As a consequence of this different attitude toward potentiality, it is possible for power structuralists to adopt a different metaphysical stance toward the temporal parts of the Bohmian particle configuration. I noted earlier that the difference between presentism and four-dimensionalism can be framed in terms of whether an object that persists through time is grounded in its temporal parts, or whether the object grounds its temporal parts (see Section 2.3). For the Super-Humean, the particle configuration is grounded in the sum of its temporal parts, which consist of one set of distance relations followed by another. So the truth about the laws of nature must also be grounded in the sum of its temporal parts. For the power structuralist, by contrast, the power-atoms are more fundamental than the temporal parts of the configuration, which are generated through the exercise of their powers. Consequently, the whole truth about the laws of nature is grounded in the power-atoms at *any* moment of time. Nonetheless, neither the Schrödinger dynamics of the wave function, nor the guiding equation of Bohmian mechanics, is grounded in any intrinsic features of the power-atoms. Rather, in this semi-Humean model, the power-atoms change their velocities in a law-like way as a brute matter of fact. (I shall return to the subject of the *lawfulness* of these Bohmian laws presently.)

### iv. *Physical properties*

Power structuralism, like Super-Humeanism, denies that the properties to which our best physical theories refer, like the physical properties of mass and charge, are intrinsic properties of microscopic particles (or fields). Such properties enter into the account solely through the dynamical role they play in describing regularities in the distribution of matter. Unlike Super-Humeans, however, who adopt an extremely *sparse* ontology of matter points, power structuralists embrace the existence of an *abundant* ontology of causal powers, regarding each power-atom as being equipped with its own unique and essential multi-track power.

Power structuralism thus appears to take a nominalist stance toward properties, since it claims that there are as many properties as there are particles in the universe. Nonetheless, we can still consider power-atoms as tokens of a common type, since the difference between each of the power-atom's powers is only a *quantitative* difference, which pertains to the temporal rate at which power-atoms change their positions. By abstracting away from this difference we can identify a *qualitative* essence that all of the power-atoms share: namely, the *potential* to change the distance relations in which they stand. It is this abstract metaphysical essence that characterises the power-atoms as the *matter* underlying all physical change.

### v. *Advantages of power structuralism*

Power structuralism, like Super-Humeanism, adopts a primitive ontology approach to quantum mechanics, positing a primitive ontology of matter governed by the laws of Bohmian mechanics. This solves the problem of non-locality. However, by enriching the supervenience base of these laws to include causal powers, power structuralism gains certain explanatory advantages over Super-Humeanism.

First, power structuralism overcomes the symmetric worlds argument, which threatens the strong structuralism of Super-Humeanism (see Section 4.3). This problem arises because particles in symmetric configurations are not individuated in a world in which they are constituted solely by distance relations. By contrast, power structuralism adopts a weak form of structuralism in which the fundamental constituents of nature have haecceities, and the powers of the power-atoms are defined concretely with reference to these primitive identities.

Secondly, power structuralism avoids the temporal dilemma, which threatens the truth of the Bohmian law of motion (see Section 4.4). This tension arises for Super-Humeans who adopt presentism whilst rejecting the existence of necessary connections. On the one hand, presentism excludes facts about future time-slices from the supervenience base. On the other hand, Humeans cannot allow past time-slices to determine the content of future time-slices. Yet the laws of nature are supposed to depend upon the positions of the particles for all time. Fortunately, there is no comparable tension in the power structuralist's account. On the one hand, a supervenience base that contains power-atoms includes facts about all the *potential* configurations of the power-atoms for all time. On the other hand, power structuralism is compatible with presentism and incorporates an arrow of time, since the power-atoms are 'directed' toward their future potentialities, and they manifest their future potentialities by exercising their powers.

Thirdly, power structuralism avoids the persistence dilemma, which calls into question the Super-Humean's commitment to a particle ontology (see Section 4.5). This difficulty is generated by combining presentism with a strong form of structuralism, such that nothing fundamentally persists between one time-slice and the next. Power-atoms, on the other hand, have what it takes to secure the persistence conditions for Bohmian particles that follow continuous trajectories through space, since they have primitive identities and bring about accidental change in their positions through the exercise of their powers.

Power structuralism is thus able to overcome all the problems I identified with Super-Humeanism in Chapter 4. It does so by rejecting strong structuralism and lifting the Humean embargo of necessary connections. Nonetheless, by adopting an ontology of powers, whilst maintaining a commitment to Humean laws of nature, power structuralism produces some counter-intuitive results.

## §5.3. The cyclic cosmos objection

My first objection concerns an implausible modal consequence that follows from the claim that particles have intrinsic powers of motion that are stimulated solely by the distance relations in which they stand. It is, as far as I know, an original objection to the idea of particles having 'Bohmian dispositions'.

### i. *Argument*

Suppose $Q_t$ represents the configuration of particles at some moment of time $t$. In a cyclic cosmos, $Q_t$ will be identical to the configuration after $n$ periods of duration $T$, ie. $Q_t = Q_{nT+t}$, where $n$ is any positive integer. According to power structuralism, the velocity of a power-atom at any moment of time depends instantaneously upon the whole configuration at that time. It follows that, once the power-atoms assume a spatial configuration they have assumed before, they will also assume the velocity profile of that earlier configuration. This presents us with no difficulties in the case of a cyclic cosmos in which every configuration that occurs within a period $T$ is *distinct* from every other configuration in this period.

However, consider the possibility of a cosmos in which the process of expansion is temporally symmetric to the process of contraction. We are to imagine that the cosmos starts small, expands in a 'big bang', reaches a limit of expansion, then retraces all of its steps in a 'big crunch', returning to the initial conditions of the particle configuration. More precisely, we shall require that $Q_{nT+\Delta t} = Q_{(n+1)T-\Delta t}$, where $\Delta t < T/2$ is some interval of time that is less than the length of half a period. Let us choose the period of the cosmos in which $n = 0$. Since the cosmos is expanding in the interval $t \in (0, T/2)$, we know that the velocity profile $v_1$ of the configuration at $\Delta t$ must be such that the particle configuration is expanding.

However, since the cosmos is contracting in the interval $t \in (T/2, T)$, the velocity profile $v_2$ at $T - \Delta t$ must be such that the configuration is contracting.

The problem is this: according to power structuralism, since the two configurations at these distinct moments of time are identical, they must have identical velocity profiles $v_1 = v_2$, whilst in a cyclic and temporally symmetric cosmos, their velocity profiles must be exactly opposite: $v_1 = -v_2$. So it is not possible for the configuration to undergo a process of expansion and contraction, in which the process of contraction is a mirror image of the process of contraction. An argument against power structuralism can be formulated as follows:

*Cyclic-cosmos argument:*

i. Suppose there is a possible world that is cyclic whose expansion and contraction periods are symmetric.

ii. If power structuralism is true, then it is impossible for cyclic worlds to have expansion and contraction periods that are symmetric.

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iii. Therefore, power structuralism is false (by i & ii).

The first premise asserts a possibility of Bohmian mechanics: the laws are compatible with the possibility of two spatially identical particle configurations instantiating non-identical velocity profiles at different moments of time. For example, Bohmian mechanics permits the possibility of a cosmos with a time-periodic wave function, $\Psi(t) = \Psi(t + T)$, in which the particle configuration recapitulates earlier phases of motion. The second premise draws out an implication of the metaphysical model in question. According to power structuralists, the manifestation of the multi-track power of each power-atom depends only upon the instantaneous spatial configuration of the other power-atoms. It is therefore impossible for two identical configurations of power-atoms to have different velocity profiles at different times, and it is therefore impossible that a cyclic world should exist. This results in a contradiction.

### ii. *Discussion*

We might attempt to modify this model so that the manifestations of the powers of the power-atoms depend on their configurations in the past, or that they incorporate distinct powers that manifest during different time intervals. In that case, a spatially identical configuration of power-atoms could instantiate different velocity profiles at different times. I shall briefly consider three ways of achieving this time-sensitivity, none of which I find satisfactory.

First, the model might be modified by abandoning any commitment to presentism and replacing a spatial configuration of power-atoms that stand in distance relations with a spatiotemporal arrangement of power-atoms that are embedded in spacetime. In that way, two spatially identical but temporally distinct configurations might stimulate different tracks. Yet if the power-atoms are eternally embedded in spacetime, in what sense do their powers underwrite change in space across time?

Secondly, the model might be modified to give each power-atom its own 'clock', in the form of a property or state that admits a new value with each co-manifestation. On the one hand, this modification would not require power structuralists to embrace four-dimensionalism. On the other hand, such a modification is *ad hoc* and strains credulity: not only would power structuralists require us to accept a simultaneity relation grounded in a privileged present, but to believe in the existence of an absolute time that is constituted by the book-keeping habits of particles.

Thirdly, we might allow that power-atoms have two multi-track powers that are mirror images of one another: the first is a type-A power to be moved with velocity $v$ given configuration $Q$, and the second is a type-B power to be moved with velocity $-v$ given configuration $Q$. The power-atoms might flip from collectively manifesting type-A powers to collectively manifesting type-B powers during the course of cosmic history, solely as a matter of chance. However, this switching mechanism does not correspond to anything in the physical theory of Bohmian mechanics: it is an *ad hoc* modification that fails to square with the determinism of Bohmian mechanics.

Alternatively, we could try to rule out the possibility of a cyclic cosmos. Yet it is difficult to see how such a ruling could be motivated. Whilst some philosophers have argued that spatially symmetric configurations are, in fact, inconceivable (see Section 4.3), there seems to be no equivalent argument for denying the conceivability of one particle arrangement being repeated at another moment of time. Moreover, models of a 'big crunch' are actively being explored in contemporary cosmology. All things being equal, we should favour a metaphysical model that does not rule out such possibilities. Thus the cyclic cosmos objection, although not insurmountable, seems to add to the theoretical costs of power structuralism, whichever way we turn.

## §5.4. The small-world objection

My second objection concerns another implausible modal consequence of power structuralism, which follows from adopting a Humean conception of laws. It applies equally well both to power structuralism and Super-Humeanism.

### i. *Argument*

According to power structuralism, the wave function is not part of the primitive ontology, nor is the Schrödinger equation grounded in any intrinsic facts about power-atoms. Rather, the Bohmian law of motion is part of a 'best systems' account of how power-atoms are distributed in space. The problem I wish to discuss is that a world that consists of only a small number of power-atoms is a world whose supervenience base is too impoverished to support the superstructure of a wave function that evolves according to the Schrödinger equation. According to the Mill-Ramsey-Lewis approach to lawhood, it is true to say that a generalisation is a law if and only if it is an axiom of the 'best systems' that 'balance[s] strength and simplicity' in deriving the facts [Callender and Cohen, 2010, p.433]. In a small world, however, there will always be some simpler account of the facts than the Schrödinger equation. According to these criteria, we should accept the generalisation offered by this simpler account, instead of asserting the truth of a law specified by Bohmian mechanics. An argument against power structuralism can thus be formulated:

*Small-worlds argument:*

i. Suppose there are only two particles in a world governed by laws specified by Bohmian mechanics.

ii. If power structuralism is true, then a world with only two particles is not governed by laws specified by Bohmian mechanics.

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iii. Therefore, power structuralism is false (by i & ii).

The first premise takes the limiting case of a small world with only two power-atoms in a possible world governed by a law specified by Bohmian mechanics. The second premise draws out an implication of the metaphysical model in question: according to the power structuralist's conception of a law of nature, the law specified by Bohmian mechanics cannot be true in a small world, since it will be possible to specify a law that is simpler than a law that includes both the Schrödinger equation and the guiding equation in its specification. According to power structuralism, then, such a world could not possibly exist, which results in a contradiction.

As an illustration of a situation involving two particles in which we can specify a law that is simpler than the law specified by Bohmian mechanics, consider the textbook example of a particle in a circular orbit around an atom, where the polar angle $\theta$ parameterises its position on this two-dimensional ring. In this case, the wave function that solves the Schrödinger equation satisfies a periodic boundary condition: $\psi(\theta) = \psi(\theta+2\pi)$. At the lowest energy level of this quantum system it can be shown by an exact calculation that the wave function does not depend upon time. However, in a world that contained nothing besides this arrangement of particles, it is evident that the Schrödinger equation, which depends upon time, would fail to be 'law-like' according to the Mill-Ramsey-Lewis criteria, because a much simpler law would be true instead: namely, one in which it is stipulated that the wave function is constant. Hence the power structuralist must insist, counterintuitively, that a world in which the wave function is constant, but is not nomologically fixed, is metaphysically impossible.

### ii. *Instrumentalist laws*

I shall consider two ways one might defend power structuralism from this charge. The first way is to reject the first premise by denying that laws are the sorts of things that get to be 'true' in the first place. As Cartwright observes, for the philosopher who thinks that laws do not literally 'govern' what goes on in the world, such as those who take Humean views of laws, 'it is an additional piece of metaphysics to suppose that there are *true* generalizations about the facts' [Cartwright, 2017].[4] In the light of these considerations, power structuralists might avoid being drawn into a debate about how large the world has to be in order for the law of Bohmian mechanics to be true by abandoning the attempt to account for the *truth* of any nomological description. They might settle for an instrumentalist construal of the laws of nature instead. According to this view, a 'law' is simply part of a useful instrument for prediction, and the Schrödinger equation, whilst useful in some worlds, is not true in any of them.

However, an instrumentalist attitude toward laws is not an option for a power structuralist who seeks to maintain a realist attitude toward quantum physics. According to this model, the power-atoms comprising its primitive ontology are the referents of the guiding equation of Bohmian mechanics, which determines the evolution in their relative positions. Insofar as these power-atoms are part of the supervenience base upon which this law depends for its truth, power structuralism retains its grip upon scientific realism. This grip is relinquished, however, by adopting instrumentalism: if this law is not true, why should we suppose it requires *truthmakers* that exist independently of our preferences and practices? In other words, why should we think that Bohmian mechanics has a primitive ontology?

### iii. *Conflicting intuitions*

A second way one might seek to respond to this argument is by complaining that it begs the question against Humeanism. If the world were different – in this case, if there were fewer particles – then the laws of nature would be different *tout court*. For the Humean, the laws do not *govern* what takes place in the world, in the sense of making anything happen, but merely *describe* in a simple but informative way its general patterns and regularities. Indeed, the governing conception of laws is intimately connected to the notion of natural necessities that thoroughgoing Humeans famously reject in their ontology. The small-worlds argument, however, presupposes a governing conception of laws, which is precisely what philosophers who take a Humean view of laws of nature are supposed to reject [Beebee, 2000].

This dismissal, however, seems too hasty. Rather than simply begging the question against Humeanism, the small-world argument, I suggest, serves as an intuition pump in considering the question of what is *accidental* and *essential* to a Bohmian cosmos. As Van Fraasen observes, 'To say that we have the concept of a law of nature must imply at least that we can mobilize intuitions to decide on proffered individual examples' [van Fraassen, 1989, p.46]. Consider, for example, Einstein's field equations in the General Theory of Relativity. If we believe these laws to be true, then we believe it is possible for the universe to be 'open' or 'closed': the laws of nature admit either of these possibilities. In other words, it seems to be accidental rather than essential to a cosmos that supports these laws of nature that it should be open or closed. Likewise, to believe that the laws of Bohmian mechanics are true, I suggest, is to believe that particles wobble their way through space in accordance with an equation of motion that depends on a wave function which satisfies the Schrödinger dynamics. These laws admit the possibility of a world with many particles and a time-varying wave function, as well as a world with only three particles and a wave function that remains constant. The number of particles and the actual wave function are accidental rather than essential features of a Bohmian cosmos.

To pose such questions is not to assume a governing conception of laws from the outset. The Mill-Ramsey-Lewis account acknowledges a metaphysical distinction between *true* laws of nature, which support counterfactuals, from *accidental* regularities, which in general do not, and aims to capture this distinction by requiring a law to be an axiom or theorem in the best system that balances strength and simplicity in deriving the facts. The difficulty that arises for the Mill-Ramsey-Lewis account, in this context, is that this purely logical distinction fails to capture our intuitions of what is essential and accidental to being a Bohmian world. As a consequence, power structuralists find themselves insisting, counterintuitively, that a Bohmian world in which the wave function is constant is metaphysically impossible.

The reason the Mill-Ramsey-Lewis account fails to capture these intuitions, I suggest, is that, in seeking to make laws purely descriptive, it reverses the proper order of explanation. According to this account, the Bohmian law of nature, which is supposed to explain such phenomena as non-local measurement outcomes in quantum experiments, depends for its lawfulness upon the global configuration of particles, and is thus constituted (in part) by that which it seeks to explain. However, as Armstrong complained in his famous critique of Humean regularity theories, 'a fact cannot be used to explain itself' [Armstrong, 1983, p.40]. In making this claim, Armstrong echoes Plato's insight that such things must be referred to a 'higher principle'. In more contemporary parlance: for one thing to explain another, we should require there to be some 'metaphysical distance' between them [Bird, 2007, p.195]. The Mill-Ramsey-Lewis account not only fails to maintain this distance, but reverses the proper order of explanation. Laws are supposed to explain instances that fall under them. In this model, however, the lawfulness of laws is grounded in the instances they are supposed to explain.

## §5.5. Argument from scientific realism

My third objection is a general concern about the compatibility of scientific realism with the Mill-Ramsey-Lewis conception of laws that is exacerbated by primitive ontology approaches to quantum mechanics, like Super-Humeanism and Bohmian power structuralism.

### i. *Argument*

I have adopted a realist posture toward quantum mechanics, in which it is part of a tradition of scientific inquiry whose goal is to give a true description of a world that exists independently of our preferences and practices. According to the Bohmian interpretation of quantum mechanics, the truth in question pertains to a law of nature that refers to a particle configuration.

In offering an account of the truth of this law, the power structuralist adopts a reformed version of the Mill-Ramsey-Lewis view of lawhood, in which a true generalisation is a law just in case it is an axiom of the best system that balances 'strength' and 'simplicity' in deriving the facts [Callender and Cohen, 2010, p.433]. The relevant facts, in this case, pertain to the relative positions of the Bohmian particles. The worry that arises for this account may be expressed in Lewis's own words: 'when we ask where the *standards* of simplicity and strength and balance come from, the answer may seem to be that they come from us' [Lewis, 1994, p.479].[5]

On the one hand, we should have no difficulty in acknowledging that scientific knowledge is generated by means of practices that are influenced by social and cultural factors, that what we discover depends on certain preferences that shape our observations and experiments, and that any knowledge distilled by such methods is fallible and subject to revision. On the other hand, in order for it to be possible for scientific inquiry to uncover truths about a world that exists independently of our preferences and practices, it cannot be the case that such factors determine the *content* of whatever we learn about nature through scientific inquiry.

The difficulty with the Mill-Ramsey-Lewis account is that the content of any generalisation it acknowledges to be a law seems necessarily to be constituted by our preferences and practices. This dependency is evident in two ways. In the first place, this account seems to lack any objective measure of simplicity that can be used to sift between different theories. One theory might be simpler than another in terms of its mathematical vocabulary, for instance, but more complex in terms of the number of kinds of entities it postulates. Who is to say which sort of 'simplicity' is paramount? In the second place, this account lacks any definition of explanatory strength. One theory may be stronger than others in terms of its power to derive a broad range of facts, for example, yet less accurate in what it predicts than another theory of somewhat narrower scope. How should we adjudicate between the different 'strengths' of these competing theories?

In these ways, the Mill-Ramsey-Lewis account of the lawfulness of laws makes the facts about laws subjectively depend upon our preferences and practices, and in so doing, puts itself at variance with the requirements of realism. An argument against power structuralism, which can be applied also to Super-Humeanism, may be formulated as follows:

*Argument from scientific realism:*

i. It is possible for scientific inquiry to uncover laws of nature whose truth does not depend upon our preferences and practices.
ii. If power structuralism is true, then all the laws of nature depend for their truth upon our preferences and practices.

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iii. Therefore, if power structuralism is true, it is not possible for scientific inquiry to uncover laws of nature whose truth does not depend upon our preferences and practices (by i. and ii.)
iv. Therefore, power structuralism is false (by i & iii).

The first premise restates a realist commitment to the possibility of objective knowledge about nature. The second draws out an implication of the metaphysical model in question: if power structuralism is true, then the laws of Bohmian mechanics depend upon our preferences and practices in a way that ought to be ruled out by any robust commitment to scientific realism. This dependency results from the reliance of this model on the Mill-Ramsey-Lewis account of laws. The third premise and the conclusion follow from the first and second premises. The argument hangs, then, by the second premise, which turns on the claim that the Mill-Ramsey-Lewis account generates laws which illicitly depend upon our preferences and practices.

### ii. *Rigidified laws*

I will consider two possible rejoinders to this argument. First, there is Lewis's claim that we can simply 'rigidify' our definition of the laws of nature. In defending the Mill-Ramsey-Lewis account of laws, Lewis initially argued that the only sort of dependence we need guard against is a certain sort of modal dependence, as exemplified in the case of the 'ratbag idealist' who claims that, if we dislike the way the world happens to be, it is possible to change the laws of nature simply by changing the way we think about the world [Lewis, 1994, p.479]. The worry is that if lawhood is contingent on our best system, which depends in turn upon our chosen standards, then the laws of nature will also depend on our choices. This would effectively put the laws of nature on wheels, whilst placing the ratbag idealist on the driving seat.

The necessary constraints for avoiding this fanciful assertion, according to Lewis, may be secured if we 'rigidify' the definition of the laws of nature, by building into the 'best theory' of any possible world those standards of simplicity and strength arising from our present preferences and practices in the actual world. In this way, we can acknowledge that our preferences and practices might have been different, but such differences are relevant only to what the inhabitants of those possible worlds would describe as the laws of nature.

Nonetheless, whilst this approach may secure the modal independence of the laws of nature, it leaves them in the state of being explanatorily dependent upon our preferences and practices, insofar as what makes these generalisations to be laws is partly those preferences and practices that we happen to have at the present moment. However, as Koons and Pickavance point out, if it is partly our present preferences and practices that make the laws what they are, then our reliability as 'detectors' of objective laws of nature must be put into question. For one thing, it seems those preferences and practices could easily have been otherwise [Koons and Pickavance, 2017, p.57]. For another, we are given no reason to suppose any likelihood of our having been attracted toward objectively real laws, which just so happen to be rigidly defined by our present preferences and practices. The strategy of rigidification looks suspiciously like sleight of hand.

iii. *The kindness of nature*

Lewis offers a second defence of the Mill-Ramsey-Lewis account of lawhood, which is expressed in the hope that nature is 'kind' to us. Whereas the ratbag idealist seeks to put laws on wheels, Lewis claims that 'the best system will be *robustly* best' inasmuch as it will 'come out first' whatever our standards of strength and simplicity. For Lewis, these standards 'are only *partly* a matter of psychology'; he looks to the pristine world of mathematics to introduce an element of objectivity. 'It's not because of how we happen to think that a linear function is simpler than a quartic or a step function; it's not because of how we happen to think that a shorter alternation of prenex quantifiers is simpler than a longer one; and so on' [Lewis, 1994, p. 479].[6] If nature is kind to us, it will favour systems that embody these mathematical standards – even a robustly best system.

So what would it mean, metaphysically, for nature to be kind to us? According to Lewis, the whole truth about the world supervenes upon a mosaic of sparse natural properties. If nature is kind to us, this mosaic will exclude 'grusome' properties, such as the property of being observed to be green before time $t$, but otherwise being blue [Goodman, 1983]. Grusome properties are unkind to us, since they are associated with one nomic profile up until some time $t$, then change their nomic profiles after time $t$. Likewise, if nature is kind to us, this mosaic will contain a sparsity rather than an abundance of natural properties. An abundance of natural properties would frustrate our efforts to write simple mathematical laws. What is needed to secure stable laws of nature across different systems, then, and hence to secure the existence of a robustly best system of laws, is the regular co-occurence of sparse natural properties, picked from a small selection of close companions. Since assessments of simplicity, strength and balance are 'immanent' rather than 'transcendent', as Cohen and Callender have argued, being 'relative to an inventory of basic kinds or basic predicates' [p.5] [Cohen and Callender, 2009], an account that seeks fundamental laws must fasten upon a set of sparse natural properties to avoid the 'problem of immanent comparisons' [pp.5-8].

However, for this argument to get off the ground, we must admit the *existence* of this mosaic of sparse natural properties, which is precisely what those who adopt a primitive ontology approach to quantum mechanics reject (see Chapter 3). According to Super-Humeans, the kinds of properties that philosophers typically consider to be fundamental, like mass and charge, are not occurrent properties in nature, but merely part of the best system that balances strength and simplicity in describing the distribution of matter points (see Section 4.2). According to power structuralists, there are an abundance of powers – one for each power-atom in nature (see Section 5.2). Thus whether or not we accept the coherence of Lewis's appeal to nature's kindness, or modifications of this strategy that attempt to deal with the various objections that have been raised against it (eg. [Massimi, 2017]), it cannot save power structuralism or Super-Humeanism from the threat of anti-realism. According to Matarese: 'if we do not regard some [sparse natural] properties other than particle position as ontologically fundamental, it is impossible... to achieve a consensus... on what the best system may be' [Matarese, 2018, p.7].

## §5.6. General remarks

In this chapter, I have put forward a primitive ontology of quantum mechanics, called Bohmian power structuralism, which supports an ontology of particles and accommodates non-local quantum phenomena. This model offers a primitive ontology of power-atoms, which have the power to change their velocities according to their configuration. By replacing the strong form of structuralism embraced by Super-Humeanism with a *weak form* of structuralism, in which the power-atoms have haecceities, and by lifting the Humean embargo of necessary connections, by endowing the particles with causal powers, power structuralism overcomes the problems with Super-Humeanism identified in the previous chapter.

Nonetheless, I have argued that this model also runs into metaphysical trouble and cannot satisfy the requirements of realism: it is susceptible to a 'cyclic cosmos' objection, which points out an implausible modal consequence of its ontology, a 'small worlds' argument, which highlights an implausible modal consequence of its

Humean stance on laws, and an 'argument from scientific realism', which exposes its criteria for lawhood to the charge of subjectivism. The root cause of its most serious problems is that this model, like Super-Humeanism, depends upon the Mill-Ramsey-Lewis conception of lawhood, but is incompatible with an ontology of sparse natural properties that might serve as a constraint on what could be counted as the 'best system' of laws (for reasons discussed in Chapter 3). What is needed, I suggest, is a temporally universal truthmaker for the lawfulness of the Schrödinger equation that exists independently of our preferences and practices. However, since it appears that neither the Armstrong-Dretske-Tooley conception of laws, nor the Mill-Ramsey-Lewis account, are capable of providing this, we need to adopt a different account of laws (see Section 3.5). In view of this discussion, I suggest a third desideratum to guide the construction of a more adequate primitive ontology:

*Desideratum: Laws grounded in powers*
DD/III: Other things being equal, we should favour metaphysical accounts in which laws are grounded in powers.

In the following chapter, I shall offer an upgrade of this metaphysical model that aims to meet this requirement, by enriching the primitive ontology to include an additional element in which the powers of the power-atoms are ultimately grounded.

## Notes

[1]Presented by Simpson for the Medieval Philosophy Network, The Warburg Institute, London, Nov. 2017.

[2]For a discussion of power-atoms as the basic building blocks of nature, in connection with Aristotle's account of the four elements, see [Marmodoro, 2018a].

[3]On the subject of transformation, see [Marmodoro, 2017].

[4]Emphasis added.

[5]Emphasis added.

[6]Emphasis added.

Chapter 6

# A powerful cosmos

> *Listening not to me but to the Logos it is wise to agree that all things are one.*
>
> – Heraclitus

## §6.1. Powers and laws

In the previous chapter, I discussed a metaphysical model, Bohmian power structuralism, which modifies the metaphysics of Super-Humeanism. Like the Super-Humean model, it attempts to explain the existence of non-local quantum phenomena by providing a supervenience base for the laws of Bohmian mechanics. According to the Bohmian interpretation of quantum mechanics, the world is composed of a configuration of particles whose trajectories are choreographed by a universal wave function. Unlike Super-Humeanism, power structuralism endows these particles with causal powers, such that one configuration necessitates another.

This metaphysical model runs into a number of difficulties, however, in the form of a cyclic cosmos problem (Section 5.3), a small-worlds objection (Section 5.4), and the argument from scientific realism (Section 5.5). At the heart of these philosophical problems is its failure to provide a truthmaker for the *lawfulness* of the Schrödinger equation in terms of its primitive ontology, rather than in terms of our preferences and practices. This failure stems from the attempt to combine the Mill-Ramsey-Lewis account of laws with a primitive ontology approach to quantum mechanics, which removes the sparse natural properties that served as a constraint on what could be counted as the 'best system' of laws.

In this chapter, I shall consider a new, 'neo-Aristotelian' metaphysical model that modifies power structuralism by incorporating a fundamental power to choreograph the trajectories of the particles, which grounds the lawfulness of the Bohmian laws of nature. In doing so, I shall seize the second horn of the truthmaker dilemma discussed in Chapter 3, by introducing what Bell called a 'non-local beable' within the primitive ontology, in addition to the particles. I shall also discard the Mill-Ramsey-Lewis account of laws in favour of an Aristotelian-essentialist account, in which laws neither govern nor describe nature, but express the *essence* of powers [Bird, 2007, chp. 9].

## §6.2. A non-local power

In order to begin building a metaphysical model that incorporates a power that grounds the Bohmian law of motion, we must answer the following question: what *has* this power? There are two answers one might be tempted to give in response: first, we might posit the existence of a substance, in addition to the physical particles, which has a causal power to move all of the particles through physical space; secondly, we might deny that this power is manifested by an agent that is extrinsic to the particle configuration, and seek to explain how a cosmos composed of particles may be said to possess this power.

### i. *A transcendent power*

Let us consider the first option. A powerful substance that exists in addition to the power-atoms might explain the change in the velocities of the power-atoms by being the *efficient cause* of their motion. In that case, the power to choreograph their trajectories would be an active power of this substance, and the particles would have passive powers to have their velocities changed. Such an account, however, runs into an *interaction problem*, which can be generated by the question: does this substance exist in physical space, or does it transcend physical space?

On the one hand, suppose that this substance transcends physical space. We might consider adopting a dualist approach to quantum mechanics, combining the primitive ontology of Bohmian particles, which exist in low-dimensional physical space, with the existence of a wave function entity, which exists in a high-dimensional configuration space. However, if the substance is a transcendent entity that does not exist in physical space, how can it be the *efficient cause* of the motions of particles in physical space? In such a model, there could be no physical contact between the substance and the particles, and hence no physical conditions for the exercise of its causal power: such a substance would have to exercise its power necessarily, rather than contingently, and its causal influence would have to reach between two disparate realms [Esfeld et al., 2017, p.133-34].[1] In such a world, any active powers to bring about change would exist beyond physical space, and the physical world would be passive and epiphenomenal; its particles reduced to being merely a decoration of the wave function [Brown and Wallace, 2005].

This conception of nature would shift the theatre of scientific inquiry from the physical world to the transcendent realm of an eternal, immaterial, unmoved mover, which manifests its power necessarily. Such a metaphysics, however, defies certain standard assumptions of scientific inquiry I am seeking to uphold for the purpose of this discussion (cf. AI/I-III).

On the other hand, suppose this substance exists in physical space. In that case, we face a second sub-dilemma. Either this substance is a localised entity – it exists *somewhere* in space – or it is a globalised entity – it exists *everywhere* in space. If the substance is localised, then it must be further away in space from some particles than from others. In that case, the substance must defy the superluminal ban on signalling in modern physics (SBS), by exercising its causal power to choreograph simultaneously the trajectories of all of the particles. I have ruled out the possibility of such causal interactions, for the purpose of this discussion (see Chapter 3). If the substance is globalised, however, we might think of it as being a structure or field-like entity that is simultaneously in contact with all of the particles in space [Hubert and Romano, 2018]. In that case, the substance would not require a superluminal mechanism, nor need it manifest its power necessarily: the condition of it exercising its power is that it is in physical contact with all of the particles.

Nonetheless, if the particles that compose the objects of scientific inquiry are endowed merely with the passive powers to have their velocities changed by a global substance, which is not itself composed of particles, in what sense do causal relations have any place in the world of scientific inquiry, which (according to Bohmians) is composed of particles? Indeed, why should we treat the particles that compose the various systems that scientists study as if they were concrete and separate entities that exist apart from this global substance? We might simply apply Ockham's razor and treat these particles and systems as epiphenomenal instead (AI/II).[2] Since it is a guiding assumption of this thesis that the objects of scientific inquiry are real and their material parts are localised within physical space (AI/III), I shall set aside the possibility that the particles are moved by a transcendent causal power.

### ii. *An immanent power*

The second option is the one I should like to consider further in this chapter: namely, the possibility that the cosmos itself, inclusive of all of the particles, has a non-local and irreducible power to choreograph their trajectories through space, because that is the *nature* of this concrete, material cosmos. To claim that the cosmos itself has such a power would be to make an informative claim in which we would learn something about an object of scientific inquiry that rules out other possibilities: if the cosmos itself has such a power, then the distribution of particles is *not* caused by something that transcends the physical cosmos, nor is it simply imposed upon the cosmos by our own conceptual practices. Rather, it is essential to the cosmos, not merely accidental to its existence, that the particles of which it is composed should follow certain kinds of trajectories. In that case, a law of nature describing those trajectories might be said to express the *essence* of this cosmic power.

## §6.3. Power monism proposed

The core of my metaphysical model – the second of three models that I propose in this thesis – may be laid out in four axioms:

*Cosmic power monism*

PM1: There are power-atoms, which exercise causal powers to change their velocities in response to their spatial configuration.

PM2: There is a cosmic power, which grounds the causal powers of the power-atoms at each moment of time.

PM3: There is a cosmic substance composed of power-atoms and the cosmic power, which has the power to choreograph the power-atoms' trajectories.

PM4: The power-atoms are the substrate of all physical change; it is the distances between them that change.

The primitive ontology consists of the power-atoms introduced in the previous model (see Chapter 5), and a new primitive element I shall call a *cosmic power*. I call this model *cosmic power monism* ('power monism', for short). By identifying the collection of power-atoms with the particle configuration of Bohmian mechanics, and by identifying the element of cosmic power as the truthmaker for the lawfulness of the Schrödinger equation, the power monist aims to supply a supervenience base for the Bohmian law of motion, thus providing an ontology of nature that can accommodate non-local quantum phenomena (see Chapter 3).

### i. *Matter and form*

Like the power structuralist, the power monist considers physical systems to consist of self-individuated power-atoms, which have powers to change their velocities. These powers are stimulated according to the spatial configuration of the power-atoms, which is explicated in terms of their distance relations. The power-atoms instantiate a structure of distance relations because they have powers to change their velocities, which brings about change in their distance relations.

For Bohmian power structuralists, the spatial configuration of the power-atoms was sufficient to fix the velocity profile of the configuration from moment to moment: each power-atom had an essential multi-track causal power, where each track of each power was holistically individuated by the total configuration. For power monists, by contrast, the primitive ontology includes an additional entity – namely, the 'cosmic power' – which plays an essential role in grounding the powers of the power-atoms. This model modifies my original conception of power-atoms in two respects.

First, the powers of the power-atoms are not *essential* to the power-atoms: rather, they are *accidental* powers which change with time. What is essential to the power-atoms is their *potential* to bear causal powers. Secondly, the velocity powers of the power-atoms are not fundamental features of nature. Rather, they are *grounded* in the cosmic power. I shall refer to a power-atom with powers as an 'empowered' power-atom, which I shall regard as a physical object. (It is a referent of Bohmian mechanics.) This grounding relation is distinct from causal relations, such as the causal relation that may exist between one configuration and another: since the powers of the power-atoms are derivative features of the power-atoms, which are grounded in the cosmic power, they jointly depend upon both the power-atoms and the cosmic power for their existence at each moment in time (see Section 2.3).

In this model, I propose that we think of the cosmic power as a simple and fundamental particular; cf. [Koons, 2018b]. It is not *located* in physical space, along with the power-atoms, since it does not stand in any distance relations, nor is it the *efficient cause* of their motion, since they have their own powers to bring about change. Rather, the cosmic power brings about change *indirectly*, by grounding the powers of the power-atoms at each moment of time. In so doing, I shall argue, it unites itself to all of the power-atoms to compose a single substance, which *of its nature* choreographs the trajectories of the power-atoms. If the cosmic power is conceived as being united with the power-atoms to compose a single substance with a physical nature – namely, the cosmos – we can conceive of the 'non-local' power that choreographs the trajectories of the particles as an *immanent* power.

I suggest that power-atoms are analogous to the Aristotelian concept of matter (see Chapter 1). By supplying a persisting substrate with the potential to bear causal powers, the power-atoms serve as the material cause of the cosmic whole. Likewise, I suggest that the cosmic power is analogous to the Aristotelian concept of substantial form. By grounding the powers of the power-atoms that bring about change in the particle configuration, the cosmic power acts as the *formal cause* of the cosmic whole, conferring a *nature* upon the cosmic whole that is characterised by the Schrödinger equation. In this way, power monism supports the anti-physicalist principle that I proposed as a criterion for Aristotelian hylomorphism (AH3): the physical parts of the cosmos – that is, the particles with 'Bohmian dispositions' – depend for their physical nature upon the 'substantial form' of the substance of which they are integral parts. One might refer to the cosmic power, thus united with the power-atoms, as the 'cosmic form' of this substance.

### ii. *Substances and entities*

Yet how does the cosmic power *unite* itself to the power-atoms to compose a single substance? Or, as Lowe puts the question: how are we to 'justify the judgment that a new concrete object – an "addition of being" – really has been brought into existence, rather than some previously existing things merely being rearranged' [Lowe, 2012, p.236]? I do not mean to suggest that by taking several elements and simply adding another element this unites them to make a single thing. For instance, I do not think this is achieved simply by adding a special power to unite different elements (as in [Rea, 2011]). Such a solution is *ad hoc* and fails to explain in what way this plurality of elements is united [Marmodoro, 2013a]. One might be tempted instead to posit some kind of structure that glues all of the elements together (as in [Jaworski, 2016]). However, a structure in which each element is *causally connected* might be counted in many different ways, according to our explanatory interests, and as such lacks the metaphysical unity of a substance [Skrzypek, 2017, Marmodoro, 2018b].

This problem may be brought into focus by Aristotle's famous syllable regress [Metaphysics VII 17, 1041b, 2531]. As Aristotle pointed out, a syllable like 'BA' is something over and above the letters 'B' and 'A' of which it is constituted, but merely adding another element would not unify them into a single syllable. Rather, the syllable would then be composed of three elements, which would themselves have to be unified. Likewise, the flesh of an organism is not an aggregate of its basic elements (for Aristotle, 'earth' and 'fire'), since it has powers over and above its constituents, and simply adding another element of the same ontological standing would not unify these elements into flesh. What we must add is the unifying *principle* that makes the letter to be a syllable, or the elements to be flesh.

According to Marmodoro, such a principle should not be conceived as an entity in the primitive ontology, to avoid falling into the regress, but as an act of conceptual individuation, in which the ultimate constituents of reality are 're-identified' within a whole according to our explanatory interests [Marmodoro, 2018b]. Marmodoro objects to a 'plurality hylomorphism', in which the matter and form of a substance are metaphysical parts, and endorses an 'anti-plurality hylomorphism',[3] in which a substance's matter is not numerically distinct from its form. I suggest, on the contrary, that we can understand how a cosmic power that is numerically distinct from the power-atoms may unite itself to the power-atoms to compose a single substance, without falling into the syllable regress, if this power is conceived as an element of a different ontological standing that *grounds* the nature of the composite.

We might get a handle on this solution by considering an analogy suggested by Koons.[4] Suppose I imagine a 3-4-5 Pythagorean triple. The imagined triangle is a compound containing four entities: my act of imagination, and the three lines of the triangle, which are each of distinct lengths. On the one hand, there is clearly a difference between the unique way in which my act of imagination is part of the imagined triangle, and the way in which each of the distinct objects imagined (the lines) are parts. On the other hand, all four of these elements are distinct and disjoint parts of a single whole. The two sorts of elements composing this whole – namely, my act of imagination, and the three different lines – are not of the same ontological standing, since my act of imagination explains why the lines of the triangle exists in the first place. Analogously, I propose that the cosmic power is united with the power-atoms by being the *formal cause* of the cosmic whole, which confers upon the matter of the cosmos a single essence or permanent nature.

As Anne Peterson points out, objections to plurality hylomorphism, such as those of Marmodoro, contain unstated Quinean assumptions about the univocal nature of being and unity, whereas for Aristotle 'there is no such thing as just being or just unity; these terms are equivocal' [Peterson, 2018, p.3]. If there is no unity that is not 'unity under some category of being', the only way to ignite a metaphysical conflict between unity and plurality within a hylomorphic composite is to 'undermine unity under the category of being at hand' [p.6]. In this case, the relevant category is that of *substance*, and hence Marmodoro's objection to plurality hylomorphism reduces to the objection that a unified substance cannot be composed of other substances.

However, Aristotle deploys his distinction between actuality and potentiality to distinguish matter and form from substance: matter is only *potentiality* for actuality, not the substance itself, whereas form 'is related to a substance as the *actuality* of that substance – its essence, or that which makes it what it is' [p.8] (see Section 1.3).[5] Likewise, I claim that power monism is able to resist anti-pluralist objections. First, in deploying grounding relations between fundamental and derivative beings, the power monist plainly rejects a univocal notion of being in favour of Aristotle's 'equivocal' notion of being (see Section 2.3), and is at liberty to reject a univocal concept of unity as well. Secondly, power-atoms and the cosmic power are analogous to Aristotle's concepts of matter and form in the relevant respects. Neither of these elements is a physical substance. The power-atoms are not physical substances because they lack causal powers apart from the cosmic power. The cosmic power is not a physical substance because it confers a physical nature upon the power-atoms, transforming them into the integral parts of a single whole.

Marmodoro's brand of anti-plurality hylomorphism also contains corpuscularian assumptions about the physical world that power monism rejects. According to Marmodoro, the world consists of primitive power-tropes, like spin and charge, which are intrinsic properties of particles picked out by our best physics. I have argued that these features are not intrinsic properties of particles nor elements of the primitive ontology (see Chapter 5). For Marmodoro, a hylomorphic substance can only be generated if its physical constituents are, so to speak, dissolved into a unity, where this subjective transformation is affected by 'a holistic re-individuation of the constituents of the structure, in accordance with either sortal or mass individuation principles' [Marmodoro, 2018b, p.66]. For power monists, however, there are *no* fundamental microphysical powers that would have to be re-individuated to generate a powerful whole (see Chapter 5). The physical powers of the whole – in this case, the cosmic whole – are not fundamental but grounded.

A structure in which one element grounds the physical nature of all the other elements has different properties from a structure of entities with their own physical natures. A structure consisting of physical entities that are causally interacting with one another may exhibit novel behaviour, but it is still an aggregate that can be counted in different ways. However, the metaphysical structure within which the cosmic power and the power-atoms are united, according to power monists, is not a causal structure in which every element is related to every other element as an efficient cause. Rather, the cosmic power is uniquely and asymmetrically related to all of the power-atoms by being the *metaphysical ground* of their causal powers at each moment of time. The cosmic power thus serves as the principle of unity of the cosmic whole, by conferring upon the cosmos a single nature, whilst being an element of a different ontological standing than the physical parts that it unites. It is an entity in its own right.[6] I shall classify it as a *metaphysical power*.

### iii. *Laws and powers*

It is in virtue of the existence of this cosmic power, and the cosmic substance that it generates, that power monism can specify truthmakers for the laws of nature that are robust against the objections to power structuralism and Super-Humeanism (see Sections 5.3-5.5). I suggest that this model does so, first, by identifying the cosmic power as the truthmaker for the lawfulness of the Schrödinger equation, and secondly, by identifying the empowered power-atoms with the physical particles to which the Bohmian law of motion refers.

I consider a law to be a general explanatory principle that supports counterfactuals. The relevant conception of lawhood in this case, however, is neither the Mill-Ramsey-Lewis account of laws, nor the Armstrong-Dretske-Tooley account. I have argued that the Mill-Ramsey-Lewis account cannot supply a primitive ontology approach to quantum mechanics with a truthmaker for the lawfulness of its laws that exists independently of our preferences and practices: this combination is susceptible to the argument from scientific realism (see Section 5.5). I have also argued that the Armstrong-Dretske-Tooley account is incompatible with a primitive ontology approach to quantum mechanics, because it conceives laws as unchanging relations that necessitate regularities between universal properties. This account cannot accommodate a law of motion that includes a wave function that changes with time, if the wave function is not part of the primitive ontology, since the properties of the wave function cannot stand in necessitation relations (see Section 3.5).

Power monism, however, adopts an Aristotelian-essentialist account of laws, in which laws are real but *grounded* in powers [Bird, 2007, chp. 9]. (For an eliminativist view of laws, which admits powers *instead* of laws, see [Mumford, 2005].) For Humeans, like Esfeld, the laws are fixed 'at the end of the world' by the Humean mosaic of local matters of fact; there is no part of that non-modal mosaic that fixes what is physically possible for any other part. For powerists, by contrast, physical modality is not grounded in anything that is non-modal, but in nature's powers to bring about change by natural necessity (see Section 2.4).

Power monism also expands the category of laws to include both *causal* and *metaphysical* laws. Following Schaffer, I take metaphysical explanation to be 'backed by grounding relations' and distinct from causal explanation [Schaffer, 2017, p.303] (see Section 2.3). Just as a causal explanation requires laws of nature to connect causes to effects, to unify natural phenomena and make them intelligible, so metaphysical explanation requires laws to connect grounds to what is grounded, for the purpose of metaphysically unifying that which is grounded. Unlike Schaffer, I take the lawfulness of laws to depend upon powers.

The existence of fundamental powers in the world embeds both causal and metaphysical explanation within an irreducibly directional (or 'teleological') context that is absent from a purely nomological description (see Chapter 2). Nonetheless, powers in nature are empirically specifiable because their manifestations have nomological profiles: the powers of the power-atoms, for example, co-manifest according to the Bohmian law of motion, which is individuated by their velocity profile $v^{\psi}$. However, the Bohmian law of motion depends on the wave function $\psi$, which is subject to change in time. According to power monism, the wave function is not a physical entity that causally interacts with the particles, nor a nomological entity that supervenes upon their distribution in space and time. Rather, the wave function may be conceived as a set-theoretic entity that individuates a *metaphysical law* in which initial distributions of power-atoms are paired with potential trajectories:

$$\langle\, \mathbf{Q}_0, \mathbf{Q}(t)\,\rangle, \quad \langle \mathbf{R}_0, \mathbf{R}(t)\,\rangle, \quad \langle \mathbf{S}_0, \mathbf{S}(t)\,\rangle, \quad \ldots$$

This law of nature is not something over and above nature's basic constituents (as in Maudlin's primitivist conception of laws [Maudlin, 2007]), nor does it merely describe a regularity observed in physical space (as in Esfeld's Super-Humean metaphysics [Esfeld and Deckert, 2017]). Rather, it expresses the *global* and *intrinsic power* of the cosmic power to impose a dynamical structure upon any particles with which it is united, which is irreducible to a single distribution of properties in physical space. This structure can be represented in configuration space, however, as a series of wave fronts which push any particles in physical space along trajectories that are perpendicular to surfaces of constant phase. In this way, the wave function may be said to represent the *dependence* of the powers of the power-atoms upon the cosmic power, at each moment of time,[7] without itself being an element of the primitive ontology. As Kim observes: 'The ontological contribution of dependence relations lies exactly in this fact: they reduce the number of independent events, states, facts, and properties we need to recognize' [Kim, 1994, p.68].

Power monism thus rejects both the Humean characterisation of the wave function offered by Super-Humeans in terms of a 'best systems' account of the particle configuration, in which the wave function is a nomological entity that supervenes upon the total configuration of matter points for all time, and the dispositional characterisation suggested by power structuralists in terms of a structural disposition of the total configuration of power-atoms, in which the disposition of each configuration changes as a brute matter of fact. In this model, the Schrödinger equation represents a metaphysical law of nature, and the wave function is a set-theoretic entity that individuates this law, whilst the Bohmian law of motion represents a causal law of nature, which expresses the intrinsic power of the cosmic substance to choreograph the trajectories of the particles that compose it.

iv. *Physical properties*

Like the Super-Humean and power structuralist, the power monist rejects the notion that microphysical properties, like mass and charge, are *fundamental* properties of particles (or fields). There is a significant difference, however, in the way these models depict the *grounding* of physical properties. For the power monist, the cosmos manifests a power to choreograph the trajectories of the particles, and the powers of the power-atoms are grounded in the cosmic power. Together, the power-atoms and the cosmic power compose a single substance with a physical nature. Power monism thus affords an alternative conception of property determination:

> *Hylomorphic property determination*
> HPD: The physical properties of a system are jointly grounded by the power-atoms composing the cosmos and its cosmic power.

This is a staunchly hylomorphic conception of the nature of physical properties:[8] the properties of being positively or negatively charged, for instance, are not intrinsic to the matter (power-atoms) of the cosmos: the motion of a power-atom through physical space may be positron-like in one part of the cosmos but electron-like elsewhere. Rather, physical properties belong to the cosmic whole: the cosmos is positively-charged-here-and-negatively-charged-there. (Power monists need not accept the dichotomy between 'global' and 'intrinsic' supposed, for example, in [Dorato and Esfeld, 2015], since they consider the cosmos to be a unified substance.)

Like the power structuralist, the power monist embraces an *abundant* ontology of causal powers, since the powers of the power-atoms are continually changing. Unlike power structuralists, however, the power monist insists on a *sparse* ontology of metaphysical powers: namely, the cosmic power, of which there is only one. However, power monism does not reduce to strict ontological monism, since the matter and form of the cosmic substance – the power-atoms and the cosmic power that together compose the cosmic whole – are numerically distinct from one another.

v. *Advantages of power monism*

Power monism, like Super-Humeanism and power structuralism, supports a solution to the problem of non-locality by providing a supervenience base for the laws of Bohmian mechanics. However, power monism offers explanatory advantages over both of its rivals. On the one hand, by adopting an ontology of power-atoms, it enjoys the same advantages as power structuralism: it can avoid the 'symmetric worlds' argument, the 'temporal dilemma', and the 'persistence dilemma' that afflict Super-Humeanism (see Chapter 4). On the other hand, by including a cosmic power in its primitive ontology, in addition to the power-atoms, it avoids the additional problems I raised for Bohmian power structuralism (see Chapter 5).

First, power monism avoids the 'cyclic cosmos' objection (See Section 5.3). This difficulty arises because quantum mechanics permits two identical particle configurations at different times to support non-identical velocity profiles. If all the manifestations of the power-atoms are 'encoded' within multi-track powers that are stimulated by their spatial configuration, it is impossible for two identical configurations to manifest non-identical velocity profiles. However, according to power monism, the velocity powers of the power-atoms are not hard-coded into the power-atoms, but are grounded in the cosmic power from moment to moment.

Secondly, power monism evades the 'small world' objection (see Section 5.4). This difficulty arises due to the fact that, if laws are merely descriptions of regularities, then it is metaphysically impossible for a world with only a few particles to support the lawfulness of the Schrödinger equation. For the power monist, however, a small world with only a few power-atoms would still contain a cosmic power, and the cosmic power is the truthmaker for the lawfulness of the Schrödinger equation.

Thirdly, power monism deflates the 'argument from scientific realism' (see Section 5.5). At the heart of this criticism is the concern that the Mill-Ramsey-Lewis account, when combined with a primitive ontology approach to quantum mechanics, leads to a subjectivist view of lawhood that is incompatible with scientific realism (AI/I). However, according to power monism, the cosmic power is both the truthmaker for the lawfulness of the Schrödinger equation *and* an element of the primitive ontology, which exists independently of any scientists, hence the lawfulness of the laws of nature does not depend upon our preferences and practices.

## §6.4. The problem of extrinsicality

Power monism affirms the fundamental significance of two scales in determining the physical properties of nature: the microsopic scale, which is the scale of the power-atoms, and the cosmic scale, which is the scale of the cosmic substance. The chief concern with power monism that I wish to raise here is an implausible modal consequence regarding *macroscopic* entities, like scientists, which it shares in common with power structuralism and Super-Humeanism.

i. *Argument*

The argument derives from an objection posed by Hawthorne against Humeanism [Hawthorne, 2004], but applies more generally to any metaphysics that implies the *thesis of extrinsicality*, which is the claim that the causal facts pertaining to any spatiotemporal region must be extrinsic to that region. To illustrate his claim, Hawthorne asks us to consider a region $R$ in which the intrusion of a bullet into the body of an organism is followed by the death of the organism. According to the thesis of extrinsicality, this region is only *extrinsically* a region in which the intrusion of the bullet into the body caused the death of the organism.

To give some precision to this claim, I shall follow Lewis in stipulating that a region $R$ has a property $P$ *intrinsically* just in case $R$ has $P$, and every possible duplicate of $R$ also has $P$. Conversely, I shall say that $R$ has $P$ *extrinsically* just in case $R$ has $P$, but it is not the case that every possible duplicate of $R$ has $P$ [Lewis, 1983, pp. 356-357]. I shall following Hawthorne in defining a causal profile $P$ to be a property that is individuated in terms of a set of causal facts $S$ about what causes what. Necessarily, an object $O$ has the causal profile $P$ if and only if all the members of $S$ are true of the object $O$. We are to think of $P$ as 'the property of being such that all the members of $S$ are true' [Hawthorne, 2004, p.354].

The thesis of extrinsicality amounts to the claim that all possible regions have all of their causal profiles extrinsically [Pallies, 2019, p. 140]. If the thesis of extrinsicality is true, then an intrinsic duplicate of any region, such as an intrinsic duplicate $R'$ of the region $R$, will not necessarily have any of the same causal profiles. $R'$ might contain a perfect duplicate of the entire country in which the organism was shot. Nonetheless, it need not be the case that the intrusion of the bullet into its body is causally connected with the death of the organism in $R'$, because $R$ does not possess any intrinsic causal profiles.

According to Hawthorne, Humeanism implies the thesis of extrinsicality, because 'the causal facts pertaining to any subregion of the world are extrinsic to that region, supervening on the global distribution of freely recombinable fundamental properties' [Hawthorne, 2004, p.351].[9] (The laws of nature are prior to the causal facts, and supervene upon nothing less than the entire Humean mosaic of non-nomological facts.) Likewise, power monism implies the thesis of extrinsicality, despite rejecting Humean conceptions of laws and causality. According to power monism, the causal powers of the objects of scientific inquiry, which are composed of power-atoms, are grounded in nothing less than the entire cosmos, which has the power to choreograph the trajectory of all of the power-atoms. Hence the causal profiles of any sub-region of the cosmos will be extrinsic to that region.

Hawthorne insists upon a connection between consciousness and intrinsicality:

it is plausible that an intrinsic duplicate of a region wholly containing a conscious being – say, the physicist Erwin Schrödinger – will contain a being that possesses the particular qualitative properties that characterise his conscious life. (For an opposing view, see [Sider, 2003].) Granted this premise, Hawthorne seeks to make trouble for the thesis of extrinsicality by arguing that there is a necessary connection between having a conscious life and having a causal profile: namely, there is some causal profile such that no being could instantiate *this* conscious life without instantiating *that* causal profile. The conjunction of these two theses contradicts the thesis of extrinsicality. This suggests the following argument against power monism:

*Argument from extrinsicality:*

i. Necessarily, an intrinsic duplicate of a region wholly containing Schrödinger will contain a being with his conscious life $L$.

ii. There is some causal profile $P$ such that a being instantiates the causal profile $P$ just in case that being instantiates the conscious life $L$.

iii. If power monism is true, then it is possible that an intrinsic duplicate of a region wholly containing Schrödinger does not contain a being that instantiates the causal profile $P$.

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iv. Therefore, if power monism is true, then it is possible that an intrinsic duplicate of a region wholly containing Schrödinger does not contain a being with his conscious life $L$ (by ii. and iii.).

v. Therefore, power monism is false (by i. and iv.).

The first premise appeals to strong intuitions: Hawthorne claims that to deny the intrinsicality of consciousness would be to throw into doubt our grasp of the concepts of intrinsicality and duplication. Indeed, one way in which two regions might *fail* to be intrinsic duplicates can be spelled out in terms of consciousness as follows: if a spatiotemporal region wholly contains a conscious being, and some other spatiotemporal region does not contain a conscious being, then these two regions cannot be intrinsic duplicates. I shall allow that the first premise is more plausible than its denial.

The second premise, which posits a necessary connection between having a conscious life $L$ and having a certain causal profile $P$, may be supported by three considerations suggested by Hawthorne. First, it seems plausible that there are essential causal relations between some phenomenal states and some attentiontional acts. Suppose, for instance, that Schrödinger is suffering from acute dyspepsia and is taking bicarbonate of soda to mitigate his symptoms. It seems reasonable to suppose that an intrinsic duplicate of a region wholly containing his phenomenal life will contain a being that is attending to feelings of dyspepsia, since it is highly implausible that a being might duplicate the phenomenal life of Schrödinger, including his feelings of dyspepsia, whilst failing to attend to any part of it. Secondly, it seems plausible that there are some essential causal relations between the temporal parts of region that supports a conscious life. Suppose the parts of that region are conceived as temporally instantaneous – that is, as lasting only for the merest instant of time. Hawthorne suggests that, for an instantaneous being, ‘there would not be enough time for the flame of consciousness to flicker’ [p.355]. In other words, it seems implausible that consciousness should be intrinsic to arbitrarily small slices of a region occupied by a conscious life $L$. It is more plausible that the consciousness of the life in this region depends upon those temporal parts being causally related in a suitable way. Finally, it seems plausible that certain phenomenal states are essentially constituted by causal powers. For example, Hawthorne suggests that phenomenal colours are *disposed* to produce certain similarity verdicts, such as the verdict that red and orange are more similar to one another than red and blue.

Such speculations will strike some philosophers more favourably than others. Here is another consideration, for those who think some kind of functionalism offers the best account of the mind. Suppose we grant that decoherence theory establishes correlations between the brain states of scientists, which are composed of particles, and the directions of pointers on their measuring devices, which are also composed of particles. Yet suppose that the macroscopic mental states of a scientist performing an experiment, which are functionally realised by microscopic particles, are not *intrinsic* either to the brain of the scientist, or the spatiotemporal region in which the experiment is being performed. In that case, we would have positive reason to doubt whether the scientist's *mental states*, which are extended over nothing less than the entire cosmos, successfully track their localised *brain states* in the right way, such that their conscious beliefs and perceptions regarding their measurements are determined by the environment of the laboratory. This poses a worry for the Bohmian solution to the measurement problem. (I shall explore such worries in Chapter 8). I shall allow, then, that we have some reasons for upholding a necessary connection between having a conscious life and having a causal profile.

The third premise articulates a corollary of power monism, which implies the thesis of extrinsicality. This claim requires some careful handling, since power-atoms do not have intrinsic physical properties, like positive or negative charge. Rather, an empowered power-atom may move in an electron-like-way in one spatiotemporal region, and in a positron-like-way in another, according to its ever-changing powers within the cosmic whole (of which it is an integral part). Nonetheless, I suggest that we can make sense of the notion of an intrinsic duplicate, in the context of power monism, if it is understood in terms of trajectories: an intrinsic duplicate of a region is one in which the relative motions of the particles in both regions are identical.

Granted the truth of the first three premises, the conclusion logically follows by deduction: certain causal facts are intrinsic to a spatiotemporal region containing a conscious being like Schrödinger, whilst power monism requires all causal facts to be extrinsic to any region. We thus obtain a contradiction. On the one hand, an intrinsic duplicate of a region that wholly contains Schrödinger should contain Schrödinger's conscious life. On the other hand, power monism, is committed to the thesis of extrinsicality, hence it permits the possibility of an intrinsic duplicate of a region that wholly contains Schrödinger yet fails to contain a being who shares his conscious life. This argument applies equally to Super-Humeanism and power structuralism. The best line of attack is to undermine the third premise.

### ii. *Profile-preserving laws*

The first line of response that I shall consider attempts to avoid the iceberg of extrinsicality by emphasising the role of local regularities over and above global regularities. Brian Weatherson has argued, in defence of Humeanism, that some spatiotemporal regions are such that all of their possible duplicates have sufficiently similar laws to support the causal profile of a conscious life [Weatherson, 2007]. According to Weatherson, it is false that a Humean conception of laws implies that all of the causal facts pertaining to a region must be *extrinsic* to that region. Whilst conceding that a region containing a conscious being like Schrödinger must possess certain properties intrinsically, Weatherson argues that the best-systems theory of laws is more sensitive to local patterns than it is to global patterns. 'If the parts are large and isolated enough... Much better to say that patterns obtaining within such a region are sufficiently simple and informative to count as laws' [p. 141]. In that case, if we accept the best-systems theory of laws, we can allow that some regions have their causal profiles intrinsically, such that their intrinsic duplicates have the same causal profiles. This argument cannot save power monism, of course, but it might give Super-Humeanism and power structuralism an advantage, since they rely on a Humean conception of laws.

Daniel Pallies has argued, however, that in a Humean world 'every possible region has duplicates such that wildly different laws pertain to those duplicates' [Pallies, 2019, p.146]. For example, let us consider the smallest spatiotemporal region in the actual world containing Schrödinger. Suppose we understand Weatherson to be claiming that every possible world containing a duplicate of the Schrödinger-region will have region-restricted laws such that its Schrödinger-region has the same causal profile as our Schrödinger-region. Pallies notes that we can generate counterexamples by considering what happens at the edges of such a region. In our world, some electron-like motions of particles, just inside the Schrödinger-region, are constantly conjoined with electron-like motions of particles, just outside the region, such that the repulsion predicted between two electrons by Coulomb's law is observed. In other possible worlds, however, those correlative motions will not be conjoined: it will be false that electrons inside the Schrödinger-region repulse electrons outside of that region. These worlds will diverge with respect to their region-restricted laws.

Alternatively, suppose we understand Weatherson to be claiming that every world containing a Schrödinger-region will have global laws that preserve the causal profiles of every Schrödinger-region. We still have reason to demur. Consider a possible world in which, for every abstract pattern of relative particle motions, up to some arbitrary number of particles, there is some set of particles in the world which realise that pattern of motion. Such a world will contains arbitrarily many Schrödinger-regions. Yet in such worlds, Pallies suggests, a Humean best-systems account of laws, in which laws are merely axioms or theorems in a true deductive system, will favour a much simpler law than those associated with the Schrödinger-region in our world: namely, 'for every abstract pattern of fundamental property and relation instantiations, there is some set of objects which realizes that pattern.' [p. 144]. If Humeans allow themselves to consider global patterns, then, as it seems that they should, they must allow that global patterns 'may defeat local patterns' [p.145], such as those patterns that obtain in the Schrödinger-region of the actual world. I conclude that Super-Humeanism and power structuralism enjoy no advantage over power monism in dealing with the problem of extrinsicality.

### iii. *Substance pluralism*

A power monist might contemplate a parallel move, however, by allowing the possibility of local metaphysical powers in nature, in addition to the cosmic power, which unite themselves to the power-atoms of particular regions to compose localised substances with intrinsic causal powers. If Schrödinger is such a substance – that is, a macroscopic entity composed of both power-atoms and a local metaphysical power – then an intrinsic duplicate of a Schrödinger-region that contains the conscious life $L$ will necessarily instantiate the causal profile $P$.

The difficulty with this proposed modification lies in finding a coherent way in which to reconcile the local contributions of these 'conscious-zone' powers with the non-local and deterministic contribution of the cosmic power, and the existence of a cosmic substance that contains all of the power-atoms with localised substances that contain sub-sets of power-atoms. The difficulties to surmount concern both the physics of the quantum dynamics and the metaphysics of substances.

First, in order for Bohmian mechanics to be true, such a world would have to be governed by Bohmian laws. Since the Bohmian law of motion is both universal and deterministic, however, there would have to be determinism at the level of any conscious-zone powers. Yet all of the Bohmian particles are quantum-entangled with one another, so the trajectories of the particles comprising a localised substance would still be choreographed by the universal wave function, and their velocities would still depend upon the positions of all the other particles. It seems the only way for a conscious-zone power to confer an intrinsic profile upon a region would be for it to violate the Bohmian law of motion. Secondly, the cosmic whole is a metaphysical substance which contains only integral and potential parts. A substance cannot contain physical substances as parts and still be a unified whole.

A more exotic possibility exists that is compatible with determinism: these metaphysical powers might influence the trajectories of the particles by acting upon the particle configuration *retroactively* and changing its initial conditions. Yet they could not do so by uniting with a local collection of power-atoms to compose a substance like Schrödinger and grounding its causal powers, but would have to causally influence power-atoms that are not part of the matter of Schrödinger. Such a world would not contain localised substances with intrinsic causal powers, nor local regions with intrinsic causal profiles. It seems, then, that 'local' metaphysical powers have no place in a Bohmian cosmos, since they would have to violate either determinism or locality in order to make a difference to the trajectories of the particles.

Suppose, then, we abandon the Bohmian interpretation of quantum mechanics, with its deterministic Schrödinger dynamics, and adopt the GRW interpretation developed by Ghirardi, Rimini and Weber [Ghirardi et al., 1986], which introduces a nonlinear stochastic mechanism for the spontaneous localisation of the wave function (see Section 3.4). We might also adopt the GRWm primitive ontology of quantum mechanics put forward by Ghirardi, Grassi and Benatti, in which the particles are replaced with a gunky matter field distribution in physical space, and the Schrödinger-evolution and collapse of the wave function correspond to expansions and contractions in its matter-density [Allori et al., 2008, Ghirardi et al., 1995].

Nonetheless, whilst these spontaneous contractions can be understood as the manifestations of causal powers [Dorato and Esfeld, 2010], this move does not succeed in pinning causal profiles to spatiotemporal regions. After all, the powers to contract the global distribution of matter density are not intrinsic to any localised physical systems, or the spatiotemporal regions in which they exist. Rather, the collapse mechanism proposed in the GRW model produces random 'hits' on the wave function that occur *universally* for microscopic particles, which do not depend upon the *local context* of the physical system. It is not sufficient, then, to deny global determinism in order to 'make room' for regions with intrinsic causal profiles. We must allow the local context of a system to make a difference to its micro-physics.[10]

## §6.5. General remarks

In this chapter, I have put forward a primitive ontology of quantum mechanics, called power monism, which accommodates non-local quantum phenomena by supplying a supervenience base for Bohmian mechanics. This model differs from power structuralism in the following respect: in addition to providing an ontology of power-atoms that have the power to change their velocities, which are the referents of the

Bohmian law of motion, this model includes a cosmic power that grounds the causal powers of the power-atoms, and in so doing supplies a truthmaker for the lawfulness of the Schrödinger equation. By adopting an Aristotelian-essentialist account of laws, in place of the Mill-Ramsey-Lewis account, this model overcomes the problems with power structuralism (see Chapter 5).

However, I argued that power monism is vulnerable to the problem of extrinsicality, which banishes intrinsic consciousness from any spatiotemporal region of the cosmos. This problem applies equally to power structuralism and Super-Humeanism. At the root of this problem, I suggest, is the fact that these metaphysical models uphold a radical form of cosmic holism, in which the only entity in nature with an intrinsic causal profile is the cosmic substance itself. In view of this difficulty, I propose a third desideratum to guide the construction of another primitive ontology:

*Desideratum: Local substances*
DD/IV: All things being equal, we should prefer metaphysical accounts in which nature contains local substances with intrinsic causal powers.

If the world consists of a single set of fundamental constituents whose micro-physics are determined by a universal wave function (MM/II), however, and the properties of every physical system are quantum-entangled, how are we to distinguish local substances with intrinsic causal powers? In the following chapters, I will argue that we have good reason to think there are systems in nature which have intrinsic properties that are not quantum-entangled, and will discuss a metaphysical model that adopts an alternative Schrödinger dynamics, in which the evolution of the wave function depends upon the local context of individual quantum systems.

## Notes

[1]Barring a fundamental randomness in the exercise of powers, which would not fit well with a deterministic Bohmian picture.

[2]This objection is analogous to one of Aristotle's objection to Platonism (see Chapter 1).

[3]To use Peterson's terminology in [Peterson, 2018].

[4]Personal correspondence.

[5]Emphasis added.

[6]In scholastic terminology: it exists *ante rem*, and not *post rem*.

[7]We might think of this abstract form of dependence as being analogous to how the motions of balls on curved surfaces depend upon the geometry of the surface.

[8]Hylomorphism is a portmanteau of the Greek words for matter (hyle) and form (morphe). For a discussion of contemporary forms of staunch vs. faint-hearted hylomorphism, see [Koons, 2014].

[9]Disputed in [Weatherson, 2007] but defended in [Pallies, 2019].

[10]I consider an alternative context-dependent quantum dynamics in Chapter 7, and a metaphysical model that includes an ontology of local substances in Chapter 9.

# Part III

# The paths to power pluralism

In Part I, I discussed how the 'hylomorphic' conception of nature, in which substances are composed of matter and form, was replaced by a micro-monist conception of nature, in which matter consists of a set of fundamental constituents described by the same micro-physics. In Part II, I discussed the challenge posed by the phenomenon of quantum-entanglement to the classical micro-monist conception of the world as consisting of particles (or fields) with intrinsic physical properties. The quantum revolution has given rise to the problem of non-locality, which is the challenge of explaining the non-local measurement outcomes of the EPR experiment, given the ban on superluminal signalling in physics (Chapter 3).

I considered three quantum micro-monist models that seek to address this problem by providing a supervenience base for the Bohmian interpretation of quantum mechanics: a Humean model, called 'Super-Humeanism' (Chapter 4), a semi-Humean, called 'power structuralism' (Chapter 5) and a 'neo-Aristotelian' model, called 'power monism' (Chapter 6). According to these models, the world consists of an arrangement of fundamental constituents – microscopic particles – governed by the laws of Bohmian mechanics, which lack any intrinsic physical properties. Yet each model seeks to improve on the previous model by conceptualising the nature of matter in a different way: for Super-Humeans, the Bohmian particles are 'matter points', which are nothing over and above the distance relations in which they stand; for power structuralists, the particles are 'power-atoms', which have powers to change their velocities; for power monists, the causal powers of the power-atoms are grounded in a 'cosmic power' that transforms them into a cosmic substance.

Among the various objections I raised against these models, I argued that: Super-Humeanism cannot provide an ontology of persisting particles, and is inconsistent in its conception of time and change; power structuralism cannot accommodate worlds with small numbers of particles or cyclic patterns of expansion and contraction, and the attempt to combine the Mill-Ramsey-Lewis view of laws with a primitive ontology approach to quantum mechanics is incoherent. Power monism avoids these problems, replacing the Mill-Ramsey-Lewis account with an Aristotelian-essential conception of laws in which the cosmic power is the truthmaker for the Schrödinger equation. Nonetheless, all three models suffer from the 'problem of extrinsicality', which excludes intrinsic consciousness from the physical world.

In Part III, I shall consider a second challenge posed to micro-monists by the emergence of thermochemical phenomena in complex quantum systems. I shall argue that the quantum micro-monist models that I considered in Part II fail to accommodate properties like temperature and chemical entropy, and should be replaced by a 'micro-pluralist' model in which the quantum micro-physics is context-dependent. I shall also argue that a micro-monist world in which the only measurable properties are determined by a universal wave function is a world in which the scientific image lacks empirical content. Finally, I shall outline a new metaphysical model called 'power pluralism', which introduces an ontology of thermochemical substances, where each substance is composed of a 'matter field' and a 'substantial power'. This hylomorphic ontology is immune to the problems I have raised for micro-monist models. This part of my thesis consists of three chapters:

Chapter 7

# Matter without microscopic constituents

*Physicists don't know what deep explanatory structure of the microworld to be realists about.*

– Roger Jones, *Realism about what?*

## §7.1. The quantum revolution in macroscopic systems

In Part II, I considered the 'quantum revolution' in microscopic physics, and the problem of non-locality to which it gave rise, which challenges the classical micro-monist conception of the world as consisting of microscopic particles (or fields) with intrinsic physical properties. I discussed a number of metaphysical models that attempt to accommodate the phenomenon of quantum entanglement by adopting a primitive ontology approach to quantum mechanics, in which the world is composed of a distribution of primitive matter without intrinsic physical properties whose arrangements in three-dimensional space (or four-dimensional spacetime) are governed by a law of nature, such as the law of motion specified by Bohmian mechanics.

Nonetheless, in this chapter I will argue that all of the ontologies that I have discussed so far undermine the possibility of scientific inquiry, since they fail to account for the macroscopic objects upon which scientists depend to perform their experiments. Clearly, it is not just *any* world in which scientific inquiry is possible. Since scientists cannot directly perceive many of the things they purport to describe, they must engage in practices in which they manipulate and observe the behaviour of macroscopic instruments. In order for scientists to manipulate these instruments, however, they must be solid objects of a certain temperature range that can be grasped by the hand, and in order for scientists to observe the positions of pointers that register their measurement outcomes, they must be colourful objects that can be distinguished visually. I shall describe such objects as having *thermochemical properties* in virtue of their instantiating 'chemical structures', which are metastable structures of chemical bonds and molecular constituents.

*Assumption of inquiry: Reality of scientific instruments*
AI/IV: The world contains macroscopic instruments that instantiate chemical structures over the time-scale of an experiment.

In a primitive ontology approach to quantum mechanics, like Super-Humeanism or power monism, the properties of a sub-system enter into the account through the *dynamical role* they play in specifying how its matter is distributed, and the measurement outcomes of a scientific experiment are constituted solely by the *positions* of the matter composing the measuring device. Yet we have good reason to doubt whether the thermochemical properties of the macroscopic objects that scientists depend upon to discern the outcomes of their experiments are reducible to the microscopic properties of a single quantum system with a universal wave function, such as a global system of particles governed by the laws of Bohmian mechanics.

In what follows, I shall argue that such 'classical' properties do not merely play a *dynamical* role in specifying regularities in a distribution of matter, such as the positions of the particles composing the pointer on a measuring device. They also play a *kinematic* role in specifying the macroscopic *boundary conditions* of any model of a system that has empirical content, in which quantum and 'classical' observables can be defined. To discuss this claim further, however, and its implications for the primitive ontology approach to quantum mechanics, we will need to consider the dynamical and kinematic structure of quantum models in a little more detail.[1]

## §7.2. The problem of emergence

### i. *From pioneer to generalised quantum mechanics*

A quantum model of a microscopic or macroscopic system has three basic components: $(\mathcal{Q}, \mathcal{S}, \mathcal{D})$. Its *observables* $\mathcal{Q}$ are variables that can in principle be measured in an experiment, such as functions of position and momentum (which embody a quantum statistical algorithm). Its *states* $\mathcal{S}$ are functionals of the observables that specify their expectation values (which are long-run experimental averages). Together, these two components comprise the system's *kinematics* $(\mathcal{Q}, \mathcal{S})$. The *dynamics* of the system $\mathcal{D}$ is given by a law that specifies the expectation value of the observables at a particular time, given the initial state of the system.

In the 'pioneer period' of quantum physics, spanning the 1930s and 40s, quantum models were primarily constructed using a Hilbert space approach (for an overview of this epoch, see [Primas, 1983], chp.3). In this model, the observables of a system are represented by a set of bounded self-adjoint operators $\mathcal{B}(\mathcal{H})$ defined in a single Hilbert space $\mathcal{H}$, whilst the states of the system correspond to density operators $\rho_t$ that determine their expectation values, which are comprised of vectors spanning the Hilbert space. Famously, these states admit superpositions, and these operators – such as those corresponding to position and momentum observables – do not commute with one another. Any interactions between a physical system and a measuring device significantly disturb the quantum state. The quantum dynamics is specified by a unitary operator defined on the Hilbert space with a fixed Hamiltonian function, which sums the kinetic and potential energies of the system. For example, in the Bohmian interpretation introduced in Chapter 3, a universal wave function for the cosmos is defined in a single Hilbert space, and a Hamiltonian may be derived for a global configuration of $N$ particles, which is idealised as applying in all contexts.[2]

In the era of quantum chemistry, which began in the 1950s, a new form of 'generalised quantum mechanics' was developed that departed from the single-Hilbert-space-approach (concerning the era of quantum chemistry, see [Primas, 1983, chp.4]). This involves constructing an algebra $\mathcal{A}$ for a quantum system using the canonical observables $\mathcal{B}(\mathcal{H})$. According to this approach, these abstract 'observables' comprise the self-adjoint part of a C*-algebra, and the 'state' corresponds to a linear mapping directly from observables to expectation values (instead of via a density function). Significantly, the states in an algebraic model can be disjoint from one another, admitting no superpositions, and a core of 'classical' (or 'global') observables can be defined which commute with one another (of which more later). These 'classical' observables are exceptions to the superposition principle, and comparatively unperturbed by measurement interactions. (I shall refer to this algebraic approach to the quantum mechanics of infinite systems as $QM_\infty$, following [Ruetsche, 2011].)

Although the algebraic approach is more general than the single-Hilbert-space-approach, a quantum theory in 'applied physics' that deploys a standard Hilbert space representation can be expanded to support functions of classical variables by taking a 'continuum limit', in which some parameter of the original model is taken to infinity. For example, in the 'thermodynamic limit', a system with $N$ particles and volume $V$ is replaced by one in which the parameters $N$ and $V$ are taken to infinity, whilst the density $N/V$ is kept constant. This procedure furnishes a model in which thermodynamic quantities, such as pressure and energy, can be represented as closed functions of thermodynamic variables, such as temperature and density.

Significantly, in this departure from the quantum mechanics of the pioneer era, thermochemical systems are treated as *infinite quantum systems*, in the sense that they have infinite degrees of freedom and contain an infinite number of sub-systems. This fact has significant implications for the physical content of infinite quantum models *viz a vis* finite quantum models, and this is the salient point to which I wish to draw attention for the purpose of this discussion. In what follows, I shall argue that infinite quantum models support states and observables that are not reducible to the states and observables of finite quantum models, and that physical systems have boundary conditions that contain irreducible macroscopic content. More broadly, I shall argue that, whilst macroscopic systems are governed by the same laws as microscopic systems, the entities and properties of such systems are metaphysically irreducible to the entities and properties of microscopic systems.

ii. *Interpretation and possibility*

It is widely supposed among analytic philosophers influenced by Wittgenstein and Lewis that to *interpret* a physical theory is to identify the set of worlds that are possible according to that theory. On this view, a possible world is to be understood as a complete and internally consistent possible state of affairs, whilst a physical theory contributes to our knowledge of nature by permitting some of these states of affairs and excluding others. It is also widely supposed that the basic laws specified by a physical theory determine the set of possible worlds that it permits: they are those complete states of affairs that are consistent with its laws.

The fundamental ontology of a theory $T$ explains what the world would have to be like for $T$ to be possible. According to *micro-monists*, as I have called them, the task of interpreting a theory is a matter of fixing upon a fundamental set of microscopic constituents and picking out their possible arrangements according to its laws (see Section 1.5). The total set of possible arrangements of these constituents constitutes the *microscopic state space* within which the microscopic constituents of every physical system evolve. Having identified these fundamental constituents, propositions that refer to reality can in principle be evaluated as true or false, just in case they can be understood as referring to possible arrangements of these constituents. On this view, as Ruetsche observes, 'everything that is physically possible must be possible in the same way' [Ruetsche, 2011, p.3]:

*Unimodal possibility*
MM/III: What is physically possible, according to some theory $T$, is determined by the set of physically possible worlds $W$ in which the laws of $T$ are true.

The notion of laws, in this case, is to be understood in the narrow sense of the laws of physics specified by the theory $T$, rather than the broad sense of laws that govern physical entities in general. Likewise, the notion of possibility is to be understood in the narrow sense of what is possible regarding the arrangements of the physical constituents to which $T$ refers, rather than the broad sense of what is possible in nature. In short, the assumption of unimodal possibility may be affirmed coherently by both reductive physicalists, who insist that everything is metaphysically reducible to the arrangements of physical constituents, and non-reductive physicalists, who insist that the ontologies of the 'special sciences' have some degree of autonomy. The assumption of unimodal possibility is narrowly concerned with the *causal closure* of their physical constituents within the microscopic state space in which they evolve.

iii. *Reduction and emergence*

According to micro-monists like Super-Humeans, the objects of scientific inquiry are composed of microscopic constituents. From a reductionist standpoint, whilst macroscopic systems may be more conveniently described by theories that invoke properties like temperature and chemical entropy, they are essentially just more of the same. This claim can be supported and made more precise by adopting something close to Ernst Nagel's account of reduction [Nagel, 1961, pp. 353-354], such as the *Nagel-Schaffner model*. Whilst this model is not without critics, it has been staunchly defended as offering the best account of a successful reduction, and it qualifies Nagel's original account in a number of significant ways. (For a recent exposition and defence, see [Dizadji-Bahmani et al., 2010].) Consider the following two theories: $T_f$, is some candidate fundamental theory, and $T_t$ is some other theory that is a target for reduction. According to this account:

*Nagelian-Schaffner reduction*
NSR: $T_t$ is reduced by $T_f$ just in case the laws of $T_t^*$ are derivable from the laws of $T_f^*$, and the terms of $T_t^*$ are associated via bridge laws with terms of $T_f^*$,

where (a) $T_t^*$ is an analogous (or approximate) version of $T_t$, and (b) $T_f^*$ is derivable from $T_f$ by means of auxiliary assumptions. The Nagelian-Schaffner model recognises that exact derivability is an unrealistic requirement: it suffices that the laws deduced from the fundamental theory should be analogous to, or approximate, the laws of the targeted theory. Likewise, the 'auxiliary assumptions' required to derive $T_f^*$ from $T_f$ are typically taken to be idealisations and boundary conditions that have no ultimate significance concerning what is possible according to the reducing theory. Having obtained $T_t^*$ as an analogous version of $T_t$, and $T_f^*$ from $T_f$ by appropriate idealisations and boundary connections, they can be connected by bridge laws. The bridge laws that enable the derivation of $T_t^*$ from $T_f^*$ constitute rules of translation which connect the vocabulary of $T_t^*$ to that of $T_f^*$. For Schaffner, a bridge law can be characterised as a 'reduction function', which offers a statement to the effect that some term $w_e$ of $T_t^*$ is coextensional with some term $w_f$ of $T_f^*$, and specifies the functional relationship between the magnitudes of the terms.

For my purposes, the dispute between a reductionist and an emergentist concerning whether macroscopic thermochemical systems are metaphysically reducible to microscopic systems can be caste as a dispute over whether the laws governing macroscopic thermochemical systems are reducible to the laws governing microscopic systems. I shall refer to this simply as *reduction*. An emergentist will seek to frustrate the reduction of theories that invoke properties like temperature and chemical entropy to microphysical theories that do not. I shall follow Jessica Wilson in distinguishing two basic schemata for emergence [Wilson, 2015]:

For *strong emergentists*, a failure in reduction is explained by the emergence of novel, 'higher-level' powers, in addition to the 'lower-level' powers of their emergence base, which influence the 'lower-level' properties of the microphysical constituents comprising the emergence base [O'Connor and Wong, 2005]. Strong emergentists deny a unimodal conception of physical possibility by affirming the reality of top-down causation, which modifies the basic dynamics of the microscopic constituents.

For *weak emergentists*, by contrast, the powers of higher-level physical entities are regarded as a subset of the powers of the lower-level constituents of their emergence base [Bedau, 1997]. The failure in reduction, in this case, may be attributed to our epistemic limitations. Weak emergentists, like reductionists, however, maintain a unimodal conception of physical possibility, affirming the supervenience of higher-level laws and properties upon lower-level laws and properties.

Reductionists, on the other hand, have argued that higher-level powers can only serve as physical causes if they are reducible to lower-level powers, in which case, they are not emergent [Kim, 1999]. It has also been argued that weak emergence is not (necessarily) incompatible with reduction [Butterfield, 2011b]. Significantly, debates between emergentists and reductionists are typically characterised by the micro-monist assumption that the emergence base is composed of a set of microscopic constituents which can be described in terms of a single semantic interpretation of our best physics (MM/II). I wish to call this assumption into question, by looking more closely at how quantum models of macroscopic physical systems are described in practice.

### iv. *The Stone-von Neumann Theorem*

The assumption that nature is composed of a single set of microscopic constituents that can be described by the same fundamental micro-physics is not metaphysically innocent, nor is the unimodal conception of physical possibility that it entails a truth universally acknowledged among philosophers of physics. To get a grip on the difficulties that arise for these micro-monist assumptions, in the context of generalised quantum mechanics, we must discuss the ideas of 'concrete representations' and 'unitary equivalence'. (For details, see [Ruetsche, 2011, chps. 2-3].)

An infinite quantum system that is described in terms of a C* algebra supports a continuum of concrete Hilbert-space representations, where a concrete representation, $\Pi(\mathcal{A}) : \mathcal{A} \to \mathcal{H}$, is a morphism from the C* algebra of the model $\mathcal{A}$ into the algebra of bounded operators defined on a Hilbert space $\mathcal{H}$. This representation makes available an 'operator topology' which defines the convergence of infinite sequences of quantum operators by using the inner product of the Hilbert space. The generation of such topologies is of interest to our discussion, because they permit the definition of 'classical' (or 'global') operators as limiting cases, which support state-dependent 'classical' observables that do not admit superpositions.

Unitary equivalence in quantum mechanics is widely considered to be the standard of physical equivalence among philosophers of physics. If two concrete representations are unitarily equivalent, there must be some unitary operator that transforms one representation into the other, such that both representations determine the same expectation values for the various observables which they define. Representations which are mutually transformable in this way are empirically indiscernible. However, the additional structure furnished by $QM_\infty$ divides finite quantum systems from infinite quantum systems in a remarkable way.

On the one hand, finite quantum systems admit one concrete irreducible Hilbert-space representation. The *Stone-von Neumann Theorem* establishes that any pairs of distinct representations of the Weyl relations, which encode the algebraic structure that any quantum theory must realise, will be unitarily equivalent to the irreducible 'Schrödinger representation', since there is a unitary operator that transforms one into the other [Ruetsche, 2011, chp.2]. This in turn implies that we can define a Hamiltonian for a finite system that uniquely specifies the dynamics. These two ways of representing a finite quantum system have the *same empirical content*.

On the other hand, infinite quantum systems admit infinitely many concrete Hilbert-space representations, which fall outside of the scope of the Stone-von Neumann theorem [Ruetsche, 2011, chp.3]. In this case, for any pair of distinct representations in this continuum, with Hilbert spaces $\mathcal{H}_1$ and $\mathcal{H}_2$ respectively, there is no unitary operator that will transform a vector in one Hilbert space, $p \in \mathcal{H}_1$, into a vector in the other space, $q \in \mathcal{H}_2$. In other words, we cannot get from a microphysical state $p$ to a microphysical state $q$ by a continuous series of microscopic changes connected by the laws of quantum mechanics, since the state spaces within which those laws operate are not physically equivalent. Nonetheless, it turns out that such unitarily inequivalent representations of quantum systems are necessary for empirically adequate descriptions of different kinds of physical behaviour.

For example, when a material undergoes a phase transition, certain 'classical' properties of the material undergo change – typically, discontinuous change – due to some change in their external conditions. An iron bar that is at thermal equilibrium, above a critical temperature $T \geq T_c$, exhibits a paramagnetic phase, in which it experiences no net magnetization. Below this critical temperature, however, it exhibits a ferromagnetic phase, in which it experiences spontaneous magnetization. This ferromagnetic phase is a quantum phenomenon that is explained in terms of the quantum spin of the particles and the Pauli exclusion principle. Significantly, at the critical temperature both the ferromagnetic and paramagnetic phases are real possibilities for this physical system, but they require inequivalent representations.

Let's take two more examples. First, consider the behaviour of helium at a critical temperature. It may exhibit a fluid phase with finite viscosity, or a superfluid phase with vanishing viscosity. (The superfluid phase is characterised as a Bose-Einstein condensation, which can be modelled using quantum mechanics.) Second, consider the behaviour of mercury at a critical temperature, in which it exhibits either a solid phase with finite electrical resistance, or a superconducting phase with vanishing electrical resistance. (The superconducting phase is characterised by the Meissner effect, which is a quantum effect involving the ejection of the magnetic field from the interior of the superconductor.) In fact, both kinds of systems in equilibrium at critical temperatures have a variety of phases available to them, which require inequivalent representations.

However, as Ruetsche points out, the statistical physics of finite systems identifies their equilibrium states with *unique* Gibbs states [Ruetsche, 2011, p.3], implying that the phase available to a system at temperature $T$ is unique for all $T$. This is contrary to what we observe in experiments. In order to offer an empirically adequate account of phenomena like phase transitions, then, we require the additional topological structure introduced in $QM_\infty$ for infinite quantum systems, which admit infinitely many concrete Hilbert-space representations. We require this much richer variety of representations in order to define all the states and observables of different complex physical systems. According to Ruetsche, it is 'only in the thermodynamic limit [that] can one introduce a notion of equilibrium that allows what the Gibbs notion of equilibrium for finite systems disallows: the multiplicity of equilibrium states at a finite temperature implicated in phase structure' [p.3].

### v. *Taking limits in physics*

The problem of emergence that realists face is that certain thermochemical phenomena observed in macroscopic (or mesoscopic) systems are inexplicable in terms of the states and observables of finite quantum mechanical models. This difficulty arises in the face of any attempt to reduce a theory of infinite quantum systems, which admit infinite degrees of freedom, to a theory like Bohmian mechanics (discussed in Part II), which admits only a finite number of degrees of freedom. For Bohmians, the measurement statistics of any experiment are explicable in principle in terms of a set of $N$ particle positions and a wave function defined in a single Hilbert space: $(\{\mathbf{Q}_1 \ldots \mathbf{Q}_N\}, \psi)$.

This problem may be brought into focus by considering the practice of taking a limit. The limits of variables are taken in physics for various reasons. For example, for a system of massive charged particles in a gravitational field, one might take the limit $G \to 0$, where $G$ is the gravitational constant, in order to isolate the contribution of charge to the forces between them. Alternatively, one might impose spatial boundary conditions on an electromagnetic field $E(x)$ by simply requiring the magnitude $E(x) \to 0$ as $x \to \infty$, for the sake of mathematical convenience. Limits may also be taken, however, to introduce new structures into a mathematical theory.

The difficulty for microphysical reductionists is that, in order to model thermochemical phenomena in macroscopic (or mesoscopic) systems, a continuum limit must be taken (such as the limit $N \to \infty$), in order to introduce the new mathematical structures that are required to represent physical possibilities that cannot be captured by any finite microscopic model. Yet in order to offer a microscopic reduction of such systems, this limit must be regarded (implausibly) as merely an idealisation or approximation for mathematical convenience, which has no bearing upon the system's physical possibilities, and no ultimate explanatory significance.

## §7.3. Beyond reduction and emergence

### i. *Extranomic possibilities*

According to the Nagel-Schaffner model of reduction, it is sufficient to establish that a macroscopic thermochemical system is governed by the same Schrödinger dynamics as a microscopic quantum system, in order to reduce a macroscopic system to a set of microscopic constituents. According to the unimodal conception of physical possibility (MM/III), the microscopic constituents of nature evolve in a universal state space determined by physical laws. These claims are intelligible, I suggest, for a world made of microscopic constituents, like the world of classical mechanics, in which there is a global configuration of particles and fields with definite properties at all times. If such entities are not grounded in anything more fundamental, but exist without further explanation, it makes sense to ignore parochial concerns, such as the boundary conditions of a physical system, and adopt a unimodal conception of physical possibility, which heeds only what is universal in space and time.

But the quantum mechanics of infinite systems, such as the instruments upon which scientists depend to conduct experiments, presents us with a difficulty. On the one hand, given the problem of emergence (Section 7.2), we have good grounds for rejecting the unimodal conception of physical possibility upon which both reductionists and weak emergentists depend. On the other hand, given the fact that thermochemical systems can be modelled as infinite quantum systems (Section 7.1), we have good grounds for rejecting the claim that thermochemical systems are generated by structural forces that emerge at higher levels and modify the basic dynamics. I intend to explore a third way of understanding the ontological status of thermochemical properties that is neither reductionist nor emergentist, but recognises that quantum mechanics requires a *plurality* of interpretations in different settings in order to discharge its explanatory duties [Ruetsche, 2011, p.11-3]. According to Ruetsche, quantum mechanics admits two stages in its interpretation.

The first stage is the domain of *primordial possibilities*, which is circumscribed by the space of algebraic states $S_A$ in the theory of $QM_\infty$, in which the self-adjoint elements of $S_A$ correspond to quantum observables that can be measured in all physical systems. At this stage, a quantum theory may be said to have indeterminate physical content concerning the *potential* states and observables of physical systems. However, this first stage leaves the truth values of propositions concerning the actual state and observables of a physical system undefined. We cannot construct an empirically successful theory if we stop at this stage. I shall call the second stage the domain of *concrete potentialities*, which concerns the behaviour of nomological machines (to adopt Cartwright's terminology). It is only in the context of a nomological machine that an empirical theory acquires determinate content regarding *actual* states and observables of a system. This is achieved by adopting an appropriate

Hilbert space representation of the C* algebra, $\Pi(A) : \mathcal{A} \to \mathcal{H}$, which specifies a W* algebra of actual observables of a particular system that can be measured empirically, and includes 'classical' observables defined as infinite limits of convergent sequences of quantum observables. These 'classical' observables comprise a core of physical magnitudes that are not quantum-entangled, which are only defined within the boundary conditions of the particular system.

According to this two-stage approach to interpretation, it would be a mistake, on the one hand, to collapse the notion of concrete potentialities into the notion of primordial possibilities. In so doing, we would undermine the empirical force of quantum mechanical explanations that scientists have contrived for a wide range of phenomena. It would also be a mistake, on the other hand, to conflate the primordial possibilities of nature with the concrete potentialities of a single nomological machine, by privileging a single semantic interpretation of quantum mechanics. In so doing, we would undermine the application of quantum mechanics to a wide range of phenomena and curtail its explanatory successes. In short, we have good reason to doubt whether the concrete potentialities of a system are fixed universally, independently of its local context. Hence we have good reason to look for modal information in the local *boundary conditions* of quantum systems, which micro-monists assume to have no significance concerning what is physically possible.

### ii. *Macroscopic boundary conditions*

For a textbook example of a microscopic system whose state space may be seen, on closer examination, to depend upon macroscopic content that is contained in its boundary conditions, consider the case of the van der Waals force between two dipoles at positions $r_1$ and $r_2$, where each dipole is comprised of electrons in motion around a positive ion, and each has an overall neutral charge. I choose this example because intermolecular bonds have sometimes been described as being nothing but a sum of van der Waals forces that is too large to compute in practice. The famous Casimir-Polder expression for the energy of a dipole-dipole system, which can be derived using normal-mode quantum electrodynamics, is of the form

$$U \propto \frac{\alpha_1 \alpha_2}{d^7}, \tag{7.3.1}$$

which depends upon the microscopic polarisabilities of the two dipoles, $\alpha_1$ and $\alpha_2$, that describe their linear response to the electromagnetic field, and upon the distance $d$ between them [Casimir and Polder, 1948]. It is sufficient for my purposes to note that this interaction energy can be derived using a quantum mechanical model of the system whose dynamics are characterised by a Hamiltonian function, and that it determines a mechanical force which arises from 'quantum fluctuations' that occur within the system even at zero temperature. These fluctuations polarise the otherwise neutral dipoles and cause them to attract one another. (For an introduction to quantum fluctuation forces, see [Simpson and Leonhardt, 2015].)

However, standard text-book expressions of the van der Waals force involve a number of significant approximations which have to be dropped in more general theories of fluctuation-induced forces, and tacitly depend upon assumptions about the macroscopic environment of the system, which are explicit in models that make more realistic predictions. For example, the Casimir-Polder expression assumes the idealised geometry of free space, but a more general expression can be derived for an environment with an arbitrary geometry, from which the Casimir-Polder expression may be recovered as a limiting case. This more general expression may be defined in terms of the Green function of the electromagnetic field $G(\omega, r, r')$, which represents the electric field response at position $r$ to a dipole source located at position $r'$, oscillating at frequency $\omega$. The interaction energy takes the form of a summation (or integration) over the micro-forces induced by fluctuations of the field at all electromagnetic frequencies. The Green function employed in more sophisticated models represents the scattering of the electromagnetic field by the materials comprising the surrounding environment. This scattering affects the micro-forces experienced at a given point in space, which determines the strength of the dipole-dipole interaction.

However, in addition to scattering the fields, the surrounding materials serve as a heat sink that absorbs the fields, and are characterised by thermal properties.[3] As electromagnetic waves propagate through these materials, they displace electromagnetic charges, and in so doing, they induce electric currents in the materials. Significantly, the dispersive (scattering) properties of a material are directly related to its dissipative (absorbing) properties:[4] for macroscopic media they are typically modelled by complex-valued electric permittivity $\epsilon(r, \omega)$ and magnetic permeability $\mu(r, \omega)$ functions, in which the real part of the function quantifies the way the field is dispersed by the medium, and the imaginary part the rate at which it is absorbed.

In order to represent the phenomenon of absorption within the theory of quantum electrodynamics, which is necessary for producing realistic predictions of Casimir forces, physicists have modelled this heat sink as an infinite continuum of oscillators, which must have uncountably many more degrees of freedom than the electromagnetic field (see [Philbin, 2010], then [Horsley and Philbin, 2014]). For the sake of empirical adequacy, there must be one oscillator for every possible frequency, at every point in space, and each of these oscillators must make an infinitesimal contribution to the dispersive and dissipative properties of the material, as characterised by its electric permittivity and magnetic permeability functions.

However, the energy does not flow out of the electromagnetic field and into the materials without coming back again. In fact, the materials heat up, then radiate the energy they have absorbed, thus contributing to the surrounding electromagnetic field. In this environment, the quantum energy levels of the microscopic molecules comprising the dipole-dipole system are thus permanently 'dressed' by the modified electromagnetic field, due to their interaction with their thermochemical environment. In more general theories of fluctuation-induced forces, the assumption of thermodynamic equilibrium is made explicit, in which the temperature of the total system is introduced as a 'classical' variable that affects both the amplitude of the fields and the magnitude of the currents. Significantly, this background assumption applies even in the case of systems at zero temperature.

To put the point in quantum-theoretic terms: in the most general descriptions of microscopic fluctuation forces, which includes the effects of dispersion and dissipation that are always present in any real physical system, the eigenmodes of the total quantum system are considered to be in a thermal mixed quantum state. Thus even for the idealised case of fluctuation-induced forces at zero temperature, such as the van der Waals force between two dipoles in a vacuum, which can be recovered from more general theories of fluctuation forces as a limiting case, the ground state of the total system remains one in which the thermal properties of the materials and the electromagnetic properties of the fields are inextricably coupled. Fundamentally, it is the ground state of a polariton field, in which thermalised matter and electromagnetic quanta are mixed (for further discussion, see [Simpson, 2014]).

The microscopic state space of an 'isolated' dipole-dipole system is thus seen to depend upon the macroscopic content implicit within its boundary conditions,[5] which are characterised by such properties as temperature. It would be question-begging to infer the reduction of thermochemical systems to aggregates of microscopic particles, by appealing to the reducibility of intermolecular forces to quantum fluctuation forces, when our best description of these forces is one in which macroscopic thermochemical features of the system are already implicated. To accomplish such a reduction, we would have to demonstrate how to remove these background features, rather than simply assuming their reducibility, by showing that properties such as temperature, and phenomena like dissipation, can be consistently represented within a finite quantum model. I have already suggested some reasons, however, for why a thermochemical system cannot be modelled as a finite quantum mechanical system (see Section 7.2). (For more reasons why heat sinks or heat baths cannot be represented by many-body wave functions, see [Drossel, 2017].)

## §7.4. Argument from emergence

The metaphysical models I discussed in Part II all adopt a unimodal conception of possibility (MM/IIII): specifically, they assume that the physical possibilities of nature consist of the possible arrangements of a finite set of basic constituents (MM/II). In order to motivate the construction of a new metaphysical model, which dispenses with this micro-monist assumption, I shall argue that scientific inquiry would not be possible in such a world, by drawing attention to the problem of emergence. This doubt may be formulated using the following argument:

*Argument from emergence:*

i. It is possible for scientists to make observations using scientific instruments.

ii. If it is possible for scientists to make observations using scientific instruments, then there must be macroscopic objects that instantiate chemical structures.

iii. If Super-Humeanism or power monism is true, there are no macroscopic objects that instantiate chemical structures.

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iv. Therefore, if Super-Humeanism or power monism is true, it is impossible for scientists to make observations using scientific instruments (by ii. and iii.).

v. Therefore, Super-Humeanism and power monism are false (by i & iv.).

The first and second premises of this argument constitute a precondition for engaging in scientific inquiry, reiterating the instrumentation assumption upon which such an inquiry depends (AI/IV). Since scientists do not directly perceive many of the things they purport to describe, they must rely upon macroscopic instruments, which are solid objects that fall within a certain temperature range, and colourful objects that can be discerned visually from their surroundings. Apart from the existence of macroscopic objects with the necessary chemical structures to support these physical interactions, scientists can learn nothing about the properties of microscopic objects, such as the positions of particles.

The third premise is supported by the considerations I offered above. Namely, in order to facilitate cogent theorising about chemical structures, scientific models must refer to properties like temperature and chemical entropy, which are not fundamental features of particles, and must model objects with thermochemical structures as infinite quantum systems, which have macroscopic boundary conditions. However, the Bohmian interpretation of quantum mechanics deployed by Super-Humeans and power monists stipulates the existence of a global configuration of particles with finite degrees of freedom, and the states and observables of thermochemical systems are irreducible to the states and observables of this global system of particles. This gives us reason to doubt whether chemical structures exist in a Super-Humean or power monist world. The conclusion follows by deduction from the premises.

This argument gives us another reason to think Super-Humeanism and power monism are false. To refute this argument, Super-Humeans and power monists will have to attack the third premise. A Super-Humean might do so either by denying the claim that a macroscopic object instantiates novel thermochemical properties, or affirming the claim that novel thermochemical properties of a macroscopic system can be described in terms of a single interpretation of quantum mechanics. To consider how these strategies might be advanced, I shall focus in what follows on the phenomenon of phase transitions.

In an infinite quantum model, the two phases on either side of a phase transition, 1 and 2, are described using unitarily inequivalent representations which demand different semantic interpretations, $I_1$ and $I_2$. These phases are empirically divided by a 'classical' macroscopic observable, such as the temperature $T$. In order to overcome the demand for multiple interpretations to explain these emergent phenomena, which threatens the unity of nature at the microscopic scale, the Super-Humean must insist that infinite quantum models somehow misrepresent the dynamics of thermochemical systems, or misconstrue the nature of 'classical' observables.

i. *Eliminating emergence*

The first strategy seeks to reduce the explanatory burden produced by the problem of emergence by denying that such phenomena as phase transitions are really possible. For example, Leo Kadanoff argues: 'Since a phase transition only happens in an infinite system, we cannot say that any phase transitions actually occur in the finite objects that appear in our world' [Kadanoff, 2009]. In so doing, micro-monists withhold any physical significance from those 'classical' observables that certain successful scientific practices seem to be measuring, such as temperature and chemical entropy, and deny that there are any emergent phenomena for them to explain. This strategy might be epitomised by the expression, 'nothing is different'.

However, this approach dispenses with any pretense of empiricism and comes at a high theoretical cost. First, it seems absurd to deny that water can exist in the different phases of solid, liquid and gas, for example, because our preferred interpretation of quantum mechanics cannot accommodate the macroscopic observables scientists rely upon to distinguish its different phases. Secondly, by denying that such phenomena exist to be explained, it significantly reduces the explanatory virtues of quantum mechanics that realists depend upon in order to justify their realism. The problem with eliminativism is that it acknowledges too few of the *observables* that are needed to distinguish phenomena that quantum mechanics is widely supposed to explain, and in failing to do so, undermines the motivation for adopting the eliminativist strategy in the first place [Ruetsche, 2011, chp.6].

ii. *Weakening emergence*

The second strategy seeks to shoulder the explanatory burden produced by the problem of emergence by admitting the possibility of thermochemical phenomena like phase transitions, whilst denying that such phenomena involve transitions between microphysical states that demand different semantic interpretations. For example, Jeremy Butterfield claims that reduction and (weak) emergence can be 'reconciled' by regarding the continuum limit to be nothing but an idealisation [Butterfield, 2011a, Butterfield, 2011b]. Whilst 'classical' observables, like temperature, may derive some physical significance from systems that have large numbers of particles, the different interpretations of a system's phases, $I_1$ and $I_2$, merely *approximate* what could in principle be represented by a finite model with a single interpretation $I_f$, which demands no such change: ie. $I_1 \approx I_f \approx I_2$. Nonetheless, taking the thermodynamic limit introduces new mathematical structures, which grants a certain autonomy to those systems to which they are applied. In this case, 'less is different'.

However, this approach also comes at a theoretical cost. First, by privileging a single class of unitarily equivalent representations, it fails to capture the widely accepted phenomenon of symmetry breaking involved in the occurrence of phase transitions. Secondly, by withholding physical significance from the continuum limit, it undermines the construction of any rigorous models of those macroscopic properties and relations that are constitutive of universal thermochemical phenomena, and hence fails to support the explanatory agenda of quantum mechanical theories of thermochemical systems. The problem with this attempt to secure emergence is that it acknowledges too few of the *states* that are needed to characterise phenomena that quantum mechanics is widely supposed to explain [Ruetsche, 2011, chp. 6].

iii. *Strengthening emergence*

The third strategy, which may appeal to a powerist, is to increase the explanatory resources available by admitting the 'strong emergence' of higher-level powers, in addition to the lower-level powers that characterise the emergence base. For O'Connor, a property or power $P$ is an emergent property of some composite $O$ just in case $P$ supervenes upon the properties of the parts of $O$, $P$ is not a property of any of its parts, $P$ is distinct from any structural property of $O$, and $P$ causally influences the behaviour of its parts [O'Connor, 1994]. Strong emergence thus supports the emergence of higher-level entities and properties that exercise a form of top-down causation that changes the physical dynamics, in which the 'causal influence [of a higher-level entity] is irreducible to that of the micro-properties on which it supervenes' [p.97]. This strategy boldly proclaims that 'more is different'.

Yet this approach to thermochemical phenomena also comes with a number of theoretical costs. For instance, it is unclear how supervenient downward-acting powers are supposed to arise from the microscopic constituents of the quantum system upon which they depend, and how these higher-level powers are supposed to factor into or modify the fundamental quantum dynamics to produce novel phenomena. It is also unclear how positing additional structural forces, besides the fundamental forces of physics, could shed any light upon the change in the interpretation of the micro-physics, between $I_1$ and $I_2$, or how it might illuminate the significance of the thermodynamic limit. The problem with this attempt to secure emergence is that it is unclear how it is supposed to be *applied* [Bedau, 1997, pp.376-77].

## §7.5. Grounding emergence

I propose to adopt a different strategy to any of the preceding. Following Primas and Ruetsche, I shall take the use of the continuum limit as introducing additional representational content concerning the properties of physical systems, rather than being a way of approximating the behaviour of macroscopic systems [Primas, 1983, Ruetsche, 2011]. However, instead of arguing that macroscopic systems have higher-level causal powers that somehow emerge from their microscopic constituents, in addition to the lower-level powers they are supposed to possess, I shall argue that microscopic systems are *grounded* in different macroscopic systems, and evolve within irreducibly 'classical' *boundary conditions*. This strategy, which I shall call 'micro-pluralism', is epitomised by the expression, 'the micro-physics is different'.

### i. *A hierarchical quantum state*

As Ruetsche observes, 'there is something extremist' about the idea that the interpretation of quantum mechanics should be fixed solely by general principles of metaphysics and epistemology, without reference to how scientists explain quantum phenomena in practice, and the attempt to hold onto this interpretation 'come what may' [Ruetsche, 2011, p.4]. As we have seen, the infinitely many representations permitted by $QM_\infty$ fall outside of the scope of the Stone-von Neumann theorem, yet these *physically inequivalent* representations are necessary for formulating empirically adequate accounts of the behaviour of macroscopic systems, including the macroscopic instruments that scientists depend upon to perform experiments. How can we reconcile this plurality of inequivalent representations with scientific realism?

According to George Sewell, the additional structure introduced by taking the continuum limit in the theory of infinite quantum systems can be given a *hierarchical interpretation*, where the Hilbert space in which the quantum state of a system is defined corresponds to the (essential) *macrostate* of the quantum system, whilst the vector that is defined in this Hilbert space corresponds to its (accidental) *microstate* at a given moment [Sewell, 2014, pp.4-5].[6] In this schema, two vectors that belong to the same irreducible representation are microscopically distinct but macroscopically equivalent, whilst two vectors belonging to inequivalent representations are macroscopically distinct: they are essentially different physical systems.

The microscopic wave function of pioneer quantum mechanics, which features in GRW theory and the Bohmian interpretation of quantum mechanics, is a projection of a vector (quantum state) defined in a Hilbert space $|\psi\rangle \in \mathcal{H}$ onto the finite configuration space of $N$ quantum particles, $\psi(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N) \in \mathbb{R}^N$. The wave function determines the quantal properties of this finite system of particles that can be measured in an experiment. However, from the standpoint of $QM_\infty$, there is more information about the state of an infinite system, which is not carried over into the microscopic wave function. As noted earlier, a Hilbert space representation makes available an 'operator topology' that defines the convergence of infinite sequences of quantum operators in the continuum limit. This permits a core of 'classical', macroscopic properties to be defined, within the boundary conditions of a nomological system, that characterise the system's essential macrostate.

With this in mind, let us return to the example of a phase transition in an infinite quantum system. I shall take the different interpretations of a system's phases, $I_1$ and $I_2$, to indicate a real change in the essential macrostate of a quantum system, allowing for the existence of different kinds of *ontic systems* that require unitarily inequivalent Hilbert space representations. These systems can be distinguished in practice by certain 'classical', thermochemical properties that they instantiate at the macroscopic (or mesoscopic) scale. Since these systems are governed by the same physical laws, but the state spaces in which they evolve cannot be reduced to the state space of a single microscopic configuration, I propose the following 'micro-pluralist' conception of the *concrete potentialities* of a particular system, to replace the micro-monist conception of the abstract physical possibilities of nature:

*Micro-pluralist concrete potentialities*
MP/I: The intrinsic potentialities of an ontic system $S$, according to theory $T$, are determined by the laws of $T$ *and* its essential macro-state (described by $T$).

Following Koons, I propose to take the use of the continuum limit in thermal physics and quantum chemistry as signifying an *ontological difference* between finite microscopic and infinite macroscopic systems: 'If these infinite models are to be genuinely explanatory, the use of the continuum limit has to be justified in ontological terms, and not merely as a useful fiction' [Koons, 2019]. Instead of positing the existence of strongly emergent causal powers, like O'Connor, however, I shall interpret this ontological difference in terms of the metaphysics of *grounding*, distinguishing fundamental and derivative states. (For a discussion of grounding, see Section 2.3.)

On the one hand, I shall regard the quantum states of infinite macroscopic (or mesoscopic) systems to be *fundamental ontic states*. These ontic systems have *intrinsic* physical properties that are not quantum-entangled, and they require unitarily inequivalent representations in order to model their behaviour. On the other hand, I shall regard the wave functions of finite microphysical systems – that is, systems of quantum particles – to be *derivative states*. These systems have only *extrinsic* physical properties, which are determined by the properties of the ontic system in which they are grounded and their physical boundary conditions.

Adapting Ruestche's 'harmony principle', which constrains the kinematical structure of $QM_\infty$, I shall require an ontic system to be one that maintains a dynamical relationship between a set of quantum and 'classical' observables that can be measured in an experiment, and sustains a continuity relationship in their temporal evolution [Ruetsche, 2011, pp.139-40]. To satisfy the first criterion, I shall require a concrete Hilbert space representation of the C* algebra, $\Pi(\mathcal{A}) : \mathcal{A} \to \mathcal{H}$, with a Hamiltonian that is well-defined in the continuum limit. According to this criterion, an ontic system supports law-like relationships between certain state-dependent 'classical' observables, which are defined in terms of quantum observables in the continuum limit. To satisfy the second criterion, I shall require the time evolution operators to satisfy a temporal continuity condition. This continuity condition will be violated by certain thermochemical phenomena like phase changes, which require transitions between unitarily inequivalent representations.

ii. *A context-dependent quantum dynamics*

If the thermochemical properties of ontic systems are neither epiphenomenal nor useful constructs, and if the systems they characterise are parts of the same causal nexus, they should make a *causal difference* to how these systems evolve. According to micro-pluralists, however, the causal influence of the macroscopic upon the microscopic is not like the influence of strongly emergent causal powers upon their emergence bases, which impose structural forces upon the microscopic constituents of a physical system to modify its normal behaviour. Rather, as George Ellis puts it: 'the upper levels exercise crucial influences on lower level events by setting the context and boundary conditions for the lower level actions' [Ellis, 2012, p.1896]. This *context-dependence* can be secured by adopting an appropriate quantum dynamics.

I noted earlier that there is no consensus among philosophers of physics concerning the quantum dynamics (see Chapter 3). According to Bell, any realist approach to quantum mechanics that seeks to explain the existence of definite measurement outcomes must come to terms with a nomological dilemma: either the quantum dynamics of standard quantum mechanics is wrong, and the wave function evolves according to a non-linear Schrödinger equation, or standard quantum mechanics is incomplete, and there are physical objects, in addition to the wave function, which evolve according to some non-linear dynamics of their own [Bell, 1987b].

For micro-monists, the choice comes down to two alternatives (according to [Maudlin, 1995]): either we should adopt something like the GRW theory, or something like the Bohmian interpretation (see Section 3.4). The GRW theory seizes the first horn of the dilemma by incorporating a stochastic mechanism which produces random 'hits' on the wave function that occur universally for microscopic particles, and result in the spontaneous collapse of the wave function. The effects of this non-linear modification to the Schrödinger equation become significant when a large number of quantum-entangled particles are involved. The theory of Bohmian mechanics seizes the second horn of the nomological dilemma by positing a global configuration of particles whose trajectories are choreographed by the universal wave function. The guiding equation for the particles depends in a non-linear way upon the wave function, which evolves according to the standard Schrödinger equation.

For micro-pluralists, however, who accept the existence of irreducible thermochemical properties, there is no need to follow either GRW theory or Bohmian mechanics. An alternative 'contextual' model of the quantum dynamics is available, proposed by Barbara Drossel and George Ellis, in which the interaction of a quantum system with the intrinsic heat bath of a measuring instrument plays a key role in solving the measurement problem [Drossel and Ellis, 2018]. I shall call it the *DEP model*, after Drossel, Ellis and Primas (since it has similarities to Primas' earlier proposals for solving the measurement problem [Primas, 1990a,Primas, 1990b]).

As in GRW theory, the DEP model seizes the first horn of the nomological dilemma, allowing the wave function to become localised with respect to position. It also distinguishes measurements from localisation events. Unlike GRW theory, however, the stochastic corrections that achieve these localisations do not occur *universally* for each microscopic particle, but depend upon the *local context* of a system, which includes the measuring device. In short, the DEP model incorporates a feedback loop – from the particle, via the intrinsic heat bath of the measuring device, back to the particle – which introduces non-linear terms in the Schrödinger equation. These terms are physically motivated: they can be accounted for in terms of thermodynamics and solid-state physics [Drossel and Ellis, 2018, pp.13-19].

As in Bohmian mechanics, the DEP model relies upon the effects of the environment upon the measuring process to explain why the outcomes of quantum experiments conform to standard quantum statistics and Born's rule for quantum observables. Unlike Bohmian mechanics, which outsources this problem to decoherence theory, the DEP model does not conceive any part of the environment that is relevant to the measuring process as a many-body quantum system that is subject to unitary and reversible time evolution, nor does it apply the Born Rule to certain 'classical' observables like temperature. Rather, the heat bath of an instrument is characterised as having non-zero temperature and only a limited 'memory', since it radiates irreversibly into the heat sink of its surroundings. Consequently, the DEP model does not leave the quantum system entangled with any part of its environment beyond the usual time scale of decoherence. According to the DEP model, the heat bath of the measuring instrument can serve as a bridge between quantum systems and their 'classical' environment, just so long as we are willing to reject 'the untestable and implausible claim that the environmental heat bath can be described by an infinite-precision wave function that is subject to unitary time evolution' [p.4].

The DEP model does not restore the local dynamical structure of classical mechanics, however, in which the properties of particles and fields determine the temporal evolution. The relevant local features, according to the DEP model, are not the intrinsic properties of microscopic entities, but the intrinsic 'classical' properties of thermochemical systems. Nor does the DEP model support the global kinematical structure of pioneer quantum mechanics, in which the world is assigned a universal wave function defined in a single Hilbert space. 'Quantum theory *per se* does not tell us what Hilbert spaces to use. This requires the classical, macroscopic context' [p.25]. In other words, these 'classical' properties perform a second explanatory role, besides the dynamical role played by the wave function in specifying the laws of a physical theory: namely, they specify the macroscopic *boundary conditions* within which the evolution of a physical system takes place.

### iii. *Beyond micro-monism*

The primitive ontology approaches to quantum mechanics considered in Part II, such as Super-Humeanism and power monism, seek an account of the empirical content of a physical theory that is exhausted by its statements about a primitive distribution of matter. They are micro-monist ontologies that fix upon a single semantic interpretation of quantum mechanics in terms of a single set of microscopic constituents, such as the Bohmian interpretation, and specify a law for their temporal development. The emergence of thermochemical behaviour in macroscopic systems, however, suggests that the laws of Bohmian mechanics are not true laws of nature, since thermochemical phenomena are not all described by the same micro-physics, and any nomological system for which observables are defined has classical boundary conditions that have irreducibly macroscopic content.

I have suggested a micro-pluralist approach to quantum phenomena instead, which adopts a hierarchical interpretation of quantum states in terms of both 'quantal' and 'classical' properties, in which certain macroscopic properties of a system are irreducible to its microscopic properties. The contextual theory of the quantum dynamics provided by the DEP model, although incompatible with micro-monism, is compatible with micro-pluralism, which considers microscopic systems to be grounded in macroscopic systems. Whilst the unitary part of the evolution is universal, and takes place within a given Hilbert space, the collapse of the wave function is 'determined top-down by the local classical context' [p.24]. For micro-pluralists who adopt the DEP model, 'classical' properties thus play an irreducible role in specifying the boundary conditions in which the evolution of a quantum system takes place.

I intend to offer a modified version of power monism that is compatible with micro-pluralism. Before proceeding, however, I wish to note two things. First, the *direction* of this grounding relation is exactly the opposite of the direction assumed by classical micro-monists. For classical micro-monists, the world is composed of a single set of microscopic constituents, such as particles and fields, which have intrinsic microscopic properties. According to micro-pluralists, however, microscopic properties are neither fundamental nor intrinsic physical properties (rejecting MM/I), but grounded in macroscopic systems. Secondly, the *scale* at which this relation of grounding operates is not the cosmic scale of the universal wave function supposed by quantum micro-monists, who consider the physical properties of nature to be grounded in nothing less than the entire cosmos. According to micro-pluralists, the cosmos is not composed of a single set of microscopic constituents which are described by the same micro-physics (rejecting MM/II), but contains a plurality of macroscopic systems which evolve in unitarily inequivalent state spaces.

## §7.6. General remarks

In this chapter, I discussed the problem of emergence, which is the challenge of explaining the states and observables of macroscopic thermochemical systems in terms of the states and observables of microscopic systems (Section 7.2). I rejected a unimodal conception of physical possibility (MM/III), in which the laws of physics determine all the possibilities of nature, and argued for a micro-pluralist conception of concrete potentialities (MP/I), which depend upon *both* the universal laws of physics *and* the essential macroscopic states of individual systems (Section 7.3).

I also offered an 'argument from emergence', in which I claimed that scientific inquiry would be impossible in a Super-Humean world composed of a finite set of fundamental constituents whose behaviour are governed solely by universal micro-physics (Section 7.4). This argument applies to all three of the metaphysical models I proposed in Part II. It supports the claim that we should attribute ontological significance to the practice of taking the continuum limit to describe thermochemical phenomena, such as phase transitions (Section 7.5). In seeking to obtain an *empirically adequate* account of nature, which includes both quantum entanglement and emergent thermochemical phenomena, it seems we must reject micro-monist assumptions about the world (MM/I-II). The corpuscularian conception of nature that arose to prominence in the seventeenth century, from which micro-monism descends (see Chapter 1), has been overturned by the quantum revolution of the last century. In the light of this discussion, I suggest the following desideratum:

*Desideratum: Matter without microscopic constituents*
DD/V: Other things being equal, we should favour accounts in which the matter of different thermochemical systems is not reducible to a single set of microscopic constituents that are described by the same micro-physics.

## Notes

[1]For more technical detail, see [Primas, 1983, chp.3-4] and [Ruetsche, 2011, chp.2].

[2]The wave function $\psi$ is formed by taking the inner-product of the state vector with the position operator defined on the Hilbert space. $\psi = \psi(x_1, , x_N)$ is a complex spinor-valued function defined in a finite 3N-dimensional configuration space. Although the particle configuration is posited in addition to the wave function, the extra variables that this introduces are best-described as *manifest* rather than 'hidden' variables [Maudlin, 1995, p.8], insofar as all measurements come down to position measurements, and the measurement outcome statistics of an experiment are

explicable in terms of particle positions, the Bohmian law of motion, and a probability measure defined in terms of the wave function that is linked with that law [Lazarovici et al., 2018].

[3]For an introduction to quantum fluctuation-induced forces in dispersive and dissipative materials, see [Simpson and Leonhardt, 2015].

[4]The real and imaginary parts are connected by the Kramers-Kronig relations.

[5]In the case of the Casimir force, as conceived by Casimir, these are boundary conditions imposed by the materials on the electromagnetic field.

[6]I have added the words 'essential' and 'accidental' for the sake of clarity.

## Chapter 8

# Saving the manifest image

*'When I use a word,' Humpty Dumpty said, in rather a scornful tone, 'it means just what I choose it to mean – neither more nor less.'*

– Lewis Carroll, *Through the Looking-Glass.*

### §8.1. The Canberra plan

In the previous chapter, I considered the emergence of 'thermochemical' phenomena in quantum systems, and the role of certain 'classical' properties in specifying the physical boundary conditions of any nomological machine for which observables can be defined. I proposed an ontological division between *micro-monists*, for whom the microscopic properties of a system are described by the same micro-physics, and *micro-pluralists*, for whom microscopic properties are grounded in different thermochemical systems, whose temporal development is context-dependent. I argued that micro-pluralism follows from taking an ontological stance toward the thermodynamic limit in order to secure the explanatory power of quantum mechanics.

In this chapter, I seek to bolster the case for micro-pluralism, by arguing that micro-monist ontologies, like Super-Humeanism and power monism, fail to accommodate the *manifest image* (to adopt Sellars' terminology). In other words, I think they are unable to recover the world of observation and experimentation, as it appears to scientists independently of their theoretical postulates, from the 'scientific image' of nature as it is described by quantum micro-monists. In failing to do so, I shall argue, micro-monists undermine the *empirical content* of quantum mechanics, by giving sceptics about semantic realism a positive reason to doubt whether the descriptions provided by our best physical theories succeed in *referring* to anything beyond the world of observation and experimentation.

In the Posterior Analytics, Aristotle observes that scientific inquiry must begin from the objects 'prior and better known to man' [Aristotle, Posterior Analytics, II.2]; that is, from the macroscopic objects of the manifest image. Yet the objects of the manifest image are not the fundamental elements that are postulated at the end of scientific inquiry, which are beyond our observational capacities (for Aristotle, the 'forms' that confer upon substances their physical natures; see Chapter 1). Nonetheless, as Maudlin observes, 'since the behavior of the mesoscale objects provides the empirical evidence for the physical theory, there must be not merely a heuristic ascent from the manifest image to the theoretical, but also a more logically rigorous return from the scientific image to the manifest' [Maudlin, 2019, p.1].[1]

In articulating their own primitive ontology of quantum mechanics, Ghirardi, Grassi and Benatti likewise acknowledge the need for 'a worldview which can accommodate our [empirical] knowledge about natural phenomena' [Ghirardi et al., 1995]. For example, two scientists conducting the EPR experiment must rely upon the macroscopic pointers on their Stern-Gerlach devices to indicate whether a microscopic particle is 'spin-up' or 'spin-down'. A primitive ontology approach to quantum mechanics seeks to account for these macroscopic instruments and the positions of their pointers, by offering an account of the *empirical content* of a theory that is exhausted by its statements about the primitive ontology [Maudlin, 2019].

Yet it would be pragmatically inconsistent to offer an account of our macroscopic measuring devices in terms of a microscopic arrangement of primitive matter which undermined any reasons for thinking that the objects that scientists *perceive*, and the measurement outcomes that they *believe*, are related to this arrangement in a principled way. In other words, the possibility of scientific inquiry depends upon the manifest image representing certain local features of the environment in which scientists conduct their experiments, and hence it is plausible that any ontology of nature should impose *local constraints* on the manifest image:

> *Assumption of inquiry: Content of the manifest image*
> AI/V: The manifest image has determinate content and is constrained by objective local features of the physical environment.

Many micro-monists, like Esfeld, endorse the 'Canberra plan' for physics, which aims to locate everyday concepts of the manifest image, like knowledge, belief, free will and conscious experience, within the causal nexus of the microphysical world, by adopting *Ramsey Sentence functionalism* (for more details, see [Menzies and Price, 2008]). For Esfeld, the scientific image concerns the set of particles of which everything is made. This strategy has been subject to criticisms from various quarters [Halvorson, 2019, chp.8]), and Esfeld's 'Super-Humean' endorsement comes with various qualifications [Esfeld, , forthcoming]). I do not propose to discuss such details here. My object is to argue that micro-monist approaches to quantum mechanics, like Super-Humeanism and power monism, undermine this plan, by removing any local constraints on the manifest image and providing a hostage to the sceptic about reference.

## §8.2. Realising scientific practices

### i. *From functionalism to the Canberra plan*

Lewis's functionalist philosophy of mind arose out of the rubble of philosophical behaviourism in the 1960s. Whilst abandoning the attempt to explicitly define psychological properties in terms of physical properties, the functionalist project aimed to show how they could nonetheless remain anchored in the physical world by being defined in terms of the *role* they play in a physical theory. For Lewis, it is Ramsey sentences which best explicate the functional definitions that this project requires [Lewis, 1970]. Lewis's recipe consists of two stages.

First, suppose we are seeking a theory of some property in terms of something we take to be better understood, or with which we are more familiar. In that case, we should distinguish between the original and familiar terms $O$, and the new terms $P$ for which we are seeking an analysis. Suppose $O$ consists of predicates describing overt physical behaviour, whilst $P$ describes psychological states, and suppose we have a theory $T$ that consists of a single sentence, $P(c) \rightarrow O(c)$, for some constant $c$. $T$ may be understood as saying that $O(c)$ obtains whenever $P(c)$ obtains. According to Lewis's account, the $P$-terms 'stand in specified causal (and other) relations to entities named by $O$-terms, and to one another' [Lewis 1999]. To form the Ramsey sentence, we replace the $P$ terms in the postulate $T(P(c))$ with variables over which the sentence is said to quantify: $\exists x(x(c) \rightarrow O(c))$. The Ramsey sentence, $\exists x T[x(c)]$, says there is an $n$-tuple of entities satisfying the postulate. In other words, there is a realisation of the theory $T$.

Second, Lewis offers a way of identifying the referents of functionally defined terms whose causal roles we assign *a priori*, such as desires and beliefs, by identifying them with the physical occupants of their causal roles, which are discovered by scientists *a posteriori*. Having obtained the Ramsey sentence for desires and beliefs, we are at liberty to settle the metaphysics of what underlies our 'folk psychology', by reflecting upon the description of the world offered by physics. 'The core of the second stage of Lewis's program is that what the first stage provides, in effect, is a non-trivial target for empirical investigation: in this case, investigation of what it is, in fact, that plays the causal role' [Menzies and Price, 2008, p.6].

By the 1980s, the connection between functionalism and Ramsey sentences was well-established [Shoemaker, 1981]. The Canberra plan extends Lewis's functionalist programme to incorporate other features of the manifest image, including moral and aesthetic properties that make up 'folk morality' and 'folk aesthetics'. The goal is nothing less than a comprehensive naturalism in which all the apparently disparate features of the world are anchored within the Ramsey sentence of the total physical theory of the world. In what follows, I will consider how the manifest image is supposed to be recovered in the neo-Humean world envisaged by Lewis, and will consider the difficulty of applying this recipe within a primitive ontology approach to quantum mechanics, which departs from neo-Humeanism in significant ways.

ii. *Ramseyfying folk ontology*

The analytic functionalism of David Lewis offers an attractive candidate for relating the scientific image of our best theories to the manifest image of observation and experimentation [Lewis, 1972, Lewis, 1970]. According to functionalists, all entities and features of the manifest image, such as the sensible properties of macroscopic instruments used in an experiment, are reducible in principle to a set of functional roles which are realised solely by elements of the scientific image, such as the particles of Bohmian mechanics. According to Lewis, these functional properties are to be identified with the result of Ramseyfying our 'folk ontology' and the 'special sciences' in the language of our best physics.

On the one hand, the language of folk ontology refers to the sensible properties of macroscopic entities, like colour and texture. On the other hand, the language of quantum mechanics refers to such things as 'particles' and a 'wave function' defined in an abstract configuration space. I will deploy a model-theoretic version of Ramseyfication, which adopts a model for this restricted language that represents this fundamental level of reality. By extending an 'interpretation function' associated with this fundamental model, we may obtain a model of an emergent theory that deploys an expanded language, including terms in which scientists can express their beliefs about sensible properties. If such a model of an emergent theory exists, we shall consider ourselves to have good reason for regarding the ontology of this theory to be derivative. (For an introduction to 'model theory', see [Button and Walsh, 2018].) This metaphysical project turns on a critical assumption:

*Unimodal realisation*
MM/IV: The scientific image of the world is an object in the universe of sets, in which the manifest image of the world is functionally realised.

Granted this assumption (at least, for now) a fundamental theory $T_f$ may be presumed to admit a set-theoretic model $M_f$. To construct this model, we shall adopt the following general recipe. Since we wish to make reference to dispositions that may or may not be actualised, this model will be associated with a restricted set of possible worlds $W_f$, one of these worlds is designated as the actual world $w^* \in W_f$, and the semantics of dispositions understood in terms of subjunctive conditionals, such that if $\phi$ were true, $\psi$ would be true. Following Lewis's analysis of counterfactuals [Lewis, 1973], $W_f$ consists of nested spheres of possible worlds centred on $w^*$. This structure is generated by imposing a relation of comparative similarity upon the different possible worlds. Our model must also contain a restricted set of individuals $D_f$, partitioned into possible worlds, and an interpretation function $I_f$, which is used to interpret the predicates, function symbols, and singular terms of the language $L_f$, by mapping each of them to sets of entities belonging to $D_f$.

The interpretation function should work along the following lines. For any constant $c$ in the language $L_f$, $I(c)$ is a function of worlds that maps to individuals in $D_f$, such that $I(c)(w)$ is a member of $D_f(w)$ in the world $w \in W_f$. For any $n$-place predicate relation between individuals $P$, in the language $L_f$, $I(P)$ is a function of worlds that maps to sets of $n$-tuples, such that $I(P)(w)$ is a set of $n$-tuples of the members of $D_f(w)$. And for an atomic sentence, $S(c_1, \ldots, c_n)$, where $(c_1, \ldots, c_n)$ are constants in $L_f$, $I(S)$ is a set of worlds in $W_f$, where world $w \in W_f$ belongs to $I(S)$ just in case the $n$-tuple $(I(c_1)(w), \ldots, I(c_n)(w))$ belongs to $I(S)(w)$. Logical connectives can be treated in terms of operations upon sets. For example, for two constituents of an atomic sentence, $\phi$ and $\psi$, joined by logical conjunction, $I(\phi \& \psi) = I(\phi) \cap I(\psi)$. The interpretation of the existential quantifier, $I(\exists x\, \phi(x))$, is given by the infinite union of the sets $I(\phi(c))$, for each constant $c$ in the language $L_f$, which is saturated with constants. In the case of the subjunctive conditional, $\phi \mathrel{\Box\!\!\rightarrow} \psi$, we shall require that $I(\phi \mathrel{\Box\!\!\rightarrow} \psi) = W_f$, just in case there is a sphere $\xi$ that contains at least one possible world in which $\phi$ is the case, and every possible world in $I(\phi) \cap \xi$ is also in $I(\psi)$; otherwise, $I(\phi \mathrel{\Box\!\!\rightarrow} \psi) = \emptyset$. In this way, the interpretation function can be used to assign truth values to logically complex formulae.

For our purposes, the model $M_f = \langle W_f, D_f, I_f \rangle$ represents the most fundamental level of reality and corresponds to the scientific image of the world. Our goal is to extend this model to include certain features of the manifest image, which I shall refer to as *emergent*. These features must include certain patterns of overt behaviour, which pertain to experimentalists engaged in their experiments, as well as certain patterns of brain activity, which pertain to their psychological states in observing their outcomes. In extending this model, we are seeking to accommodate the kind of empirical judgement necessary for discriminating between different scientific theories on the basis of the observable outcomes of experiments. Such discourse requires an appropriately expanded language.

We may proceed by extending the restricted language $L_f$ of our fundamental model to an expanded language $L_f^e$ for the emergent world by adding whatever constants, function symbols, and predicates are required to signify the various features of this non-fundamental level of reality. (From this point, I shall use subscripts to refer to the fundamental level, and superscripts to refer to the emergent level.) Our goal is to find a theory in which this emergent world is realised within the fundamental model. We shall say that a theory of the emergent world $T^e$ is realised in the fundamental model $M_f$ just in case the interpretation function $I_f$ can be extended to a new function $I_f^e$, defined for the language $L_f^e$, such that an extended model $M_f^e$ that deploys this extended interpretation function is a model of $T^e$. This realisation is effected by providing extensions for all the terms and predicates of the emergent theory $T^e$. This extension neither modifies the primitive ontology of our fundamental theory $T_f$ nor changes its laws: the emergent model $M_f^e = \langle W_f, D_f, I_f^e \rangle$ contains the same set of possible worlds $W_f$, and the same set of individuals $D_f$, as the basic model $M_f$, which is the model for our fundamental theory.

### iii. *Lewisan functionalism*

It is helpful for comparative purposes to apply this recipe to Lewis's own brand of functionalism. In this case, the model with which we must begin is informed by something like the physics and chemistry that one learns in secondary school, since Lewis himself famously declared he was 'not ready to take lessons in ontology from quantum physics' [Lewis, 1986, p.xi]. I shall call it 'school-physics', for short, and label this theory $T_{s-phys}$. As such, a basic model of $T_{s-phys}$ may include local facts about overt behaviour, including facts about certain motions of bodies caused by scientists manipulating their instruments, certain compressions and rarefactions of the air caused by verbal descriptions of their experiments, and certain patterns of brain activity caused by their perceptions of sensible properties. A model $M_f = M_{s-phys}$ of the world for the theory $T_{s-phys}$ can generate a set of basic physical facts about the world, including local facts about the environment of an experimentalist, $\tau_{s-phys}$, in the language of school-physics $L_{s-phys}$.

The emergent world, however, includes psychological facts, $\tau^{psy}$, which are not explicitly contained within $\tau_{s-phys}$. If we are to regard the psychological properties of scientists as being functionally realised by the physical properties of particles and fields, as Lewis did, then the language of $L_{s-phys}$ must be extended to a language that includes the vocabulary of psychology, $L^{psy}_{s-phys}$. Significantly, Lewis accepted that, in addition to the vocabulary of $L^{psy}_{s-phys}$, we should have a theory of 'folk psychology', $T^{folk}$, which specifies inter-level connections between the internal psychological states of scientists that are described by psychology, and the external behaviours of scientists and their experiments that are described by school-physics. This theory generates a set of psychophysical facts, $\tau^{folk}$, which have local constraints that are represented within the set of basic physical facts, $\tau_{s-phys}$.

If the facts generated by folk psychology, $\tau^{folk}$, are consistent with facts generated by school-physics, $\tau_{s-phys}$, then there exists an interpretation function, $I^{psy}_{s-phys}$, relative to which $T^{folk}$ would be realised in the basic model $M_{s-phys}$. This function can be used to define both the set of psychophysical facts, $\tau^{folk}$, and the set of psychological facts, $\tau^{psy}$. This may be achieved by identifying the interpretation function with the set of sentences $\tau^{psy}_{s-phys}$ in the language $L^{psy}_{s-phys}$ that are verified by the model $M_{s-phys}$, which includes local physical properties like mass and charge. If this interpretation function is unique, then we shall allow that a manifest image of the world with determinate content is realised within the basic model $M_{s-phys}$. The theory of folk psychology thus plays an essential role in supporting the content assumption (AI/V) by ensuring that the psychology of experimentalists is *causally* *constrained* by local facts about their environments, which are part of the basic model of reality, $M_{s-phys}$.

iv. *Bohmian functionalism*

Suppose that we now replace school-physics as our fundamental theory of reality with something like the Bohmian description of reality adopted by Super-Humeanism. In that case, we shall require our fundamental language to be that of quantum mechanics, $L_{qm}$. As before, we require a basic model, $M_{qm} = \langle W_{qm}, D_{qm}, I_{qm} \rangle$, that contains a domain of possible worlds $W_{qm}$, one of which is designated as the actual world. As before, we are seeking an interpretation function that realises the manifest image of scientists within the basic model of reality, $M_{qm}$.

Unlike the previous case, however, we cannot appeal to the theory of folk psychology to provide inter-level connections between the physical environment of scientists and their internal representations. We cannot do so because any candidates for the physical referents of such a theory would not be local and intrinsic features of an experimentalist's environment. Whilst local qualities, like mass and charge, are part of the neo-Humean supervenience basis, Bohmian micro-monists replace this mosaic with the single, uniform 'quality' of position, and require all the physical properties of the instruments that scientists depend upon for their observations to supervene upon nothing less than the global configuration of particles.

However, if Bohmian micro-monists follow Lewis in assuming the local supervenience of the psychological upon the physical, they will obtain a surprising result: if scientists are composed of particles whose physical properties supervene upon nothing less than the global configuration of particles, then their psychological properties must also supervene upon nothing less than this global configuration. This is surprising because it implies that an intrinsic duplicate of a scientist conducting an experiment may have entirely different perceptions and beliefs about the outcomes of the experiment, even though they conduct their experiments in laboratories that are intrinsic duplicates and obtain physically identical outcomes. Which of them should we trust?

The only constraint we may impose on the realisation of an emergent theory $T^e$ that contains psychological facts, in that case, is that the entities filling the functional roles in this theory must be found in the correct model of the formal language of the fundamental theory. In other words, there are no *local constraints* on the extended interpretation function $L^e_{qm}$ in the Bohmian model of the kind that arose in the realisation of folk psychology $T^{folk}$ in the model of school-physics. This appears to be the case for any micro-monist primitive ontology approach to quantum mechanics that removes the sparse natural properties required by Lewis.

Of course, a Bohmian micro-monist might deny the *local* supervenience of the psychological upon the physical (in this case, upon the positions of certain particles), along with other philosophers of mind, such as Tyler Burge and Martin Davies [Davies, 1992]. Yet this would be a curious move for anyone who adopts a primitive ontology approach to quantum mechanics. After all, the motivation for adopting a primitive ontology was to ensure that the outcomes of quantum experiments are constituted by local configurations of matter. As Ghirardi and his collaborators argued: 'This [choice] is quite natural since the definiteness, the particularity of the world of our experience, derives from our perceiving physical objects in definite places, and this is also why the prescriptions for establishing the psychophysical correspondence usually involve positions' [Ghirardi et al., 1995, p.6]. To deny the local supervenience of the psychological upon the physical, however, would be to deny that *observed* measurement outcomes are constituted by *local* configurations of particles. In that case, what is the motivation for adopting a primitive distribution of matter that can constitute local measurement outcomes, if observed measurement outcomes are in any case constituted by nothing less than the entire cosmos?

Moreover, in the absence of any such local constraints, there is no obviously preferred language to use for describing the emergent domain, which includes scientists and their macroscopic instruments, nor any obviously preferred theory of the emergent world. The theory and language of quantum mechanics, by themselves, tell us nothing about the psychological states of scientists regarding their local experiments. Likewise, the theory and language of folk psychology, by themselves, tell us nothing about the wave function or the particle configuration. Any further constraints on the emergent world must therefore arise from internal considerations, such as the logical consistency of our theory of the emergent world, and perhaps from theoretical virtues, such as elegance and simplicity.

Suppose the Bohmian micro-monist should affirm the local supervenience of the psychological upon the physical but insist that there *are* local constraints on the interpretation function. Contrary to Lewis, they may argue, these local constraints are not provided by a spatiotemporal distribution of sparse natural *properties*, like mass and charge. Rather, these local constraints are provided by the *positions* of the Bohmian particles, which constitute an alternative Humean mosaic. A suitable interpretation function is one in which the arrangement of macrophysical bodies in the manifest image corresponds to arrangements of microphysical particles in the scientific image, with respect to the primary geometric 'qualities' of position, volume and orientation. In other words, it is because there is a physical collection of particles arranged 'pointer-wise', in the vicinity of a measuring device in the manifest image, that observed experimental outcomes depend upon local configurations of particles.

Simply fixing the geometry of macroscopic objects in the manifest image, however, does not provide a *meaningful* constraint on the interpretation function. After all, scientists conducting experiments do not perceive macroscopic instruments as ghostly geometrical structures: they *feel* them to be solid objects of a certain temperature, which can be grasped by the hand, and they *see* them as possessing certain colour profiles, which distinguish them from their surroundings. Such objects instantiate chemical structures and have properties like temperature and chemical entropy (see Chapter 7). Even supposing those thermochemical properties to be reducible to quantal properties determined by the wave function, none of the properties that are constitutive of an *observed* measurement outcome are locally realised in Bohmian mechanics. All of them depend upon nothing less than the entire global configuration of particles.

Bohmians might respond that, having fixed the geometry of macroscopic objects in the manifest image, decoherence theory ensures that the persisting aggregates of Bohmian particles that occupy the places of macroscopic objects will mirror (to a significant degree) the *behaviour* of classical objects described by Newton-Maxwell physics. In that case, we might be able to form a theory of folk psychology that specifies inter-level connections between the internal psychological states of scientists and the external behaviours of the classical-like particle aggregates described by Bohmian mechanics and decoherence theory. There are reasons to reject this appeal to decoherence theory, however, which I shall discuss presently.

## §8.3. A Putnam-style permutation argument

In what follows, I mean to adapt an argument advanced in Koons' recent critique of the Everettian interpretation of quantum mechanics [Koons, 2017], which I judge to apply more generally to primitive ontology approaches to quantum mechanics, such as the Super-Humean model advocated by Esfeld. I shall argue that adopting this fundamental model of nature results in a radical indeterminacy of meaning that leaves any names, predicates, and function symbols that feature in the language of our emergent theory without determinate intensions. This can be demonstrated succinctly by mounting a Putnam-style permutation argument.

### i. *A simple permutation*

For a simple example of how Putnam's permutation argument works, let us consider a model described by Button and Walsh [Button and Walsh, 2018, chp.2]. Here our theory $T$ consists of just three atomic sentences: 'Bohr is a cat', 'Bohm is a cat', and 'de Broglie is not a cat'. We can formalise this theory by deploying a set of individuals, $D$, three constant symbols, $\{c_1, c_2, c_3\}$, a one-place predicate $C$, and the language of first-order logic, to produce the set: $\{C(c_1), C(c_2), \neg C(c_3)\}$. A simple model $M$ can then be constructed which incorporates an interpretation function $I$ that assigns natural language $L$ to the domain $D$ and the predicate $C$ as follows:

$$I(D) = \{Bohr, Bohm, de\ Broglie\}\,, \quad I(C) = \{Bohr, Bohm\}\,.$$

According to Ramsey-functionalists, we are to think of the model $M$ as explicating a reference relation that tracks our natural language $L$, and as explicating the truth of the constitutive claims of our theory $T$. $M$ explicates reference because the name 'Bohr' refers to $I(c_1)$, the name 'Bohm' to $I(c_2)$, and the name 'de Broglie' to $I(c_3)$, whilst the predicate 'is a cat' picks out the set $I(C)$. Likewise, $M$ explicates the truth of the sentence, 'Bohr is a cat', for example, because $M \vDash C(c_1)$.

Putnam has famously sought to make trouble for semantic realism by constructing permutations of such models, which are isomorphic with respect to the way in which they explicate the *truth* of sentences, but distinct with respect to the way in which they explicate *reference* [Putnam, 1977, Putnam, 1980]. For example, consider the isomorphic mapping $\sigma(D)$ which permutes the domain $D$ such that $I(\sigma(c_1)) = Bohm$, $I(\sigma(c_2)) = Bohr$, $I(\sigma(c_3)) = de\,Broglie$. This permutation induces the following rival interpretation:

$$I'(C) = I(\sigma(C)) = \{Bohm, de\,Broglie\}\,.$$

The rival model $N$ generated by this permutation function has the same domain as the original model $M$, and realises the same set of sentences, but it differs with respect to interpretation, since these sentences refer to different elements within the domain. This raises the question: what fixes reference to the basic constituents of reality? To put the question more sceptically: why should we suppose that the original model $M$ picks out the real referents, rather than the permutation model $N$? The argument is easily generalised to encompass more complicated theories of reality, assuming the world can be described as an object in the universe of sets (MM/IV). If the world can be thus described, then any theory of the world $T$ will always have a model $M$ with a domain $D$ that represents the collection of all the actually existing objects in the world.

### ii. *A trans-world permutation*

Let us return to our more complicated model of the quantum world. I have stipulated that $T^e$ is a macroscopic theory of a world that is emergent relative to the model $M_{qm}$, because there is an interpretation function $I^e_{qm}$ that extends $I_{qm}$ to the language of $T^e$, resulting in a new model $M^e_{qm}$, such that the theory $T^e$ is realised in $M^e_{qm}$. It is trivial to prove that, in the absence of additional constraints on the emergent theory, there are an infinite number of extensions of $I_{qm}$ that will also produce an extension of $M_{qm}$ relative to which $T^e$ can be verified.

Following Putnam's lead, let us take some permutation $\sigma(w)$ of the objects in $D(w)$ for some world $w \in W_{qm}$, and apply it to the interpretation $I^e_{qm}$ with respect to the interpretation of all names and predicate symbols at $w$. The resulting interpretation is also a realisation of $T^e$ in the model $M_{qm}$. In a similar way, let us construct a trans-world permutation $\Sigma(W)$, which acts on the objects of every world in $W_{qm}$, resulting in the interpretation $J^e_{qm}$. The extension of $M_{qm}$ by $J^e_{qm}$ will also be a model of $T^e$, and so $J^e_{qm}$ will also be a realisation of our emergent theory in the model $M_{qm}$. Yet $J^e_{qm}$ will be scrambled beyond recognition with respect to $I^e_{qm}$, since the system described by the emergent theory will have been realised using an entirely different set of entities across possible worlds. This algorithm is not idempotent: it can be applied any number of times to generate an infinite set of radically different interpretations: $\left\{I^e_{qm}, J^e_{qm}, K^e_{qm}, \ldots\right\}$.

### iii. *Fantastic worlds*

If functionalists and proponents of the Canberra plan are to confine themselves to this procedure for generating the manifest image from the scientific image in a world described by quantum mechanics, it follows that any predicate involving a term in our emergent language $L^e$, such as 'Alice measured spin-up', will lack determinate intensions in terms of our fundamental language $L_{qm}$. This is evident because we can always find an interpretation function in which our emergent theory of the world is true, including a theory in which 'Alice measured spin-down' instead (cf. [Frauchiger and Renner, 2018]).

By the same token, it is entirely indeterminate what such a predicate is meant to be true of, or what it is supposed to be realised by. For example, the intension of the predicate 'is a scientist' in $I^e_{qm}$ may turn out to be the intension of the predicate 'is a magician' in a scrambled permutation $J^e_{qm}$. In the absence of local constraints on the manifest image, there is no reason why an emergent theory that contains scientists and their measuring devices should be privileged over an alternative theory that refers to magicians with magical powers. In fact, there are any number of fantastic but internally consistent emergent theories $(e_1, e_2, \ldots)$ for which we might seek an interpretation. For example, the claim that 'Alain Aspect is conducting an experiment in Palaiseau' (using the interpretation $A^{e_1}_{qm}$) might just as well be substituted by the assertion that 'Gandalf is fighting a Balrog in Khazad-dûm' (using the interpretation $G^{e_2}_{qm}$). Interpretations are cheap, and without additional constraints upon the manifest image, we have good reason to suppose that one could be found in which the 'alternative facts' of a fantastic world will turn out to be true.

Indeed, a similar argument was advanced against Bertrand Russell's theory of perception by Max Newman in 1928, in which Newman noted that any collection of things can be organised so as to have a certain structure, provided that there are a sufficient number of them: 'hence the doctrine that only structure is known involves the doctrine that nothing can be known that is not logically deducible from the mere fact of existence, except ("theoretically") the number of constituting objects' [Newman, 1928]. For the 'generating relation' of the structure of the emergent world to be nontrivial, Newman concluded, something additional must be known about reality that sets it apart as a privileged interpretation.

In my earlier example of a classical world described by school-physics, this additional knowledge was put forward in the form of the theory of folk psychology, which imposed local constraints on the interpretation function by establishing inter-level connections between the subjects of psychological states (described by the emergent theory) and the subjects of physical behaviour (described by the theory of school-physics). However, as Koons observes, in a world with a universal wave function there is no physical constraint on an emergent theory that is not a holistic constraint: any behaviour is ultimately behaviour stipulated by the wave function for the cosmos as a whole [Koons, 2017]. The possibility of advancing a theory of folk psychology that offers inter-level connections is thus precluded.

iv. *Against quantum micro-monism*

We arrive, then, at the following difficulty. According to the primitive ontology approach to quantum mechanics, nature consists of a single set of microscopic constituents (MM/II), whose dynamics are determined by a universal wave function. In the absence of any local constraints upon the manifest image, however, the manifest image would be without determinate content. Yet if this were the case then – to put it starkly – we would have no empirical means of discriminating between the different ways in which the world might be interpreted by a scientist in a laboratory or a psychotic inmate of a mental hospital. The scientific image, in such a world, would be empirically empty. At the root of this problem is the radical holism that follows from applying micro-monist assumptions to the interpretation of quantum mechanics. The analytic functionalist cannot offer a principled way of relating the scientific and the manifest image when the total configuration of matter, and the entire distribution of psychological states, must be related to one another as a whole, instead of piece by covarying piece. We might encapsulate this dialectic with the following argument:

*Argument from indeterminacy:*

i. It is possible for scientists to learn facts about nature from their experiments.
ii. If it is possible for scientists to learn facts about nature from their experiments, then the manifest image must be locally constrained.
iii. If Super-Humeanism or power monism is true, the manifest image is not locally constrained.

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iv. Therefore, if Super-Humeanism or power monism is true, it is impossible for scientists to learn facts about nature from their experiments (by ii & iii).
v. Therefore, Super-Humeanism and power monism are false (by i & iv).

Once again, the first and second premises of this argument constitute a precondition for gaining knowledge by scientific inquiry: in the absence of local constraints, the manifest image would be without determinate content, and thus scientists would not learn any facts about nature by performing experiments. The third premise was adduced in the last two sections: Super-Humeans assume the truth of the Bohmian interpretation of quantum mechanics, but neither Bohmian particles nor the wave function qualify as local constraints on the manifest image. In maintaining the assumption of micro-monism, they must deny the existence of certain constraints upon the manifest image that form part of the conditions of the possibility of scientific inquiry. The conclusion follows deductively from the premises.

This argument gives us another reason to think Super-Humeanism and power monism are false, and to doubt the micro-monist assumptions about nature that they embody (MM/II-IV), which lead to radical holism when applied to the interpretation of quantum mechanics. To refute this argument, micro-monists will have to attack the third premise. They might do so either by denying the claim that the theoretical constraints on the interpretation function are insufficient for determining the manifest image, or by denying the claim that the only constraints on the manifest image are holistic constraints.

## §8.4. More theory, more properties

### i. *Theoretical constraints*

The first strategy seeks to preserve micro-monism and shoulder the explanatory burden of accounting for the manifest image. It attempts to do so by finding additional theoretical constraints that we can impose on the extended interpretation of quantum mechanics to reduce the indeterminacy of the manifest image.

#### Natural properties and causal constraints

A favoured response to Putnam's sceptical challenge, advanced by causal theorists of reference, is that his permuted models ignore the *causal relationships* that link our use of language to the world of objects – such as one's use of the word 'cat' to the world of cats. The model that should be favoured by metaphysical realists, it may be argued, is the one which respects these causal constraints. A micro-monist, however, cannot appeal to causal connections between objects or events in the manifest image as *independent* constraints. Whether or not a causal connection holds between two objects or events of the manifest image must be settled by the interpretation function.

Descriptivists, on the other hand, argue that reference obtains in virtue of *theoretical descriptions* of things that exist in the world *associating* a term of a language with a basic object or property in the world, and thus require the world to instantiate a structure of basic properties or natural kinds. Lewis, for instance, attempts to block spurious permutations by appealing to the existence of *sparse natural properties* that are locally instantiated and feature in physical laws [Lewis, 1984]. His strategy consists, first, of identifying a class of natural properties among the subsets of the world's domain, and, second, of denying that just any subset of the domain of entities picks out a genuine natural property. By enriching the background theory beyond the theory of bare sets, such that some predicate symbol $P$ *must* be assigned to some set $M(P)$, Lewis intends to make it harder for models to realise sentences. For example, consider a background theory $T_0$ which has three natural properties: the empty set, the entire world, and some proper subset of the entire world. Halvorson suggests a theory $T$ that is ruled out by this background theory [Halvorson, 2019], which includes the following axiom:

$$\exists x Px \wedge \exists y Qy \wedge \neg(Pz \wedge Qz).$$

This theory cannot be translated into the enriched background theory $T_0$, since its properties $P$ and $Q$ demand two disjoint proper subsets, whereas the background theory is furnished only with one. Nonetheless, the appeal to sparse natural properties will not protect the primitive ontology approach to quantum mechanics from referential indeterminacy for two reasons.

First, it is unlikely that the enriched background theory could be made sufficiently strong to resist every trouble-making permutation. Halvorson suggests a background theory that admits a single natural property with actual instances, and considers a theory which asserts that 'there are many gods, and there are no electrons' [p.267]. Since this theory can be translated into the background theory, this theory, although presumably false, will turn out to be true. Counterexamples for more complex background theories might similarly be contrived. L.A Paul has argued that 'there could be an alternative, equally good, mapping of terms in the language of the theory to natural properties', with the result that we obtain 'radically different interpretation for our best theory' [Paul, 2013, p.191], which can be blocked only by denying the permutability of natural kinds.

Secondly, primitive ontology approaches to quantum mechanics, like Super-Humeanism, strip away any sparse natural properties from the supervenience base. According to Super-Humeans like Esfeld, physical properties like mass and charge are merely part of the 'best system' of Humean laws that balances simplicity and strength (see Chapter 4). Likewise, for power monists, such properties are not fundamental features of nature, but grounded in the cosmos as a whole (see Chapter 6). Yet the Humean mosaic of intrinsic natural properties, instantiated as point-instances in spacetime, was not rejected by Super-Humeans and power monists without good reason: the phenomenon of quantum entanglement suggests the non-existence of such a supervenience base (see Chapter 3).

### Appeals to simplicity

Similarly, any attempt to favour models that have 'simple' interpretation functions, whatever their merits in the case of Lewisan worlds, are unlikely to prosper in Super-Humean worlds, in which there is no possibility of interpreting the language of emergent laws in terms of the language of fundamental predicates that refer to sparse natural properties (cf. Section 5.5). Any interpretation functions – including those restricted to interpretations in terms of microphysical properties, like mass and charge – are going to be extremely complicated in a Super-Humean world, and there is no obviously objective standard for making comparisons between them.

### Decoherence theory

Alternatively, one might dismiss Lewis's attempt to secure strict local supervenience as ill-conceived, yet argue that it holds nonetheless *for all practical purposes*. In classical mechanics, all the particles exert forces upon one another from arbitrary distances, yet one can typically ignore the force-fields of particles that are far apart from each other. In Bohmian mechanics, all the particles are choreographed by a universal wave function, yet one can obtain effective wave functions through the process of decoherence. The local supervenience of the properties of water upon the properties of its molecular constituents, and the local supervenience of mental properties upon physical properties, for example, might be seen to depend simply upon the existence of stable conditions that inevitably emerge in their local environments. Esfeld has argued that the manifest image can be recovered from the scientific image, even if there is a *principled* failure of local supervenience, just so long as local supervenience holds in *practice*.[2]

I alluded earlier to the appeal to decoherence theory as a possible way of constraining the extended interpretation function, in order to reduce the indeterminacy of the manifest image. Bohmian mechanics relies upon the theory of decoherence to explain how the reduced density matrix of a quantum system coupled to an environment evolves from a pure state to a mixed state that specifies the correct probabilities for possible measurement outcomes (see Section 3.4). A Bohmian micro-monist might claim that decoherence theory ensures that persisting aggregates of Bohmian particles, which occupy the places of macroscopic objects in the manifest image, will mirror the behaviour of classical objects. In that case, we might use decoherence theory as a practical constraint upon the extended interpretation function, forming a theory of folk psychology that connects the psychological states of scientists with the external behaviours of classical-like aggregates of particles.

However, there are two problems with appealing to decoherence theory in this way. First, there are empirical reasons why some physicists find decoherence an unsatisfactory theory of the effects of the environment upon local systems, insofar as it purports to be a complete theory. As Drossel and Ellis point out, decoherence theory relies on 'the untestable and implausible claim' that the thermal environment of a quantum system 'can be described by an infinite-precision wave function that is subject to unitary time evolution' [Drossel and Ellis, 2018, p.4]. In fact, there are positive reasons to doubt that this is the case [Drossel, 2017]. Secondly, decoherence theory involves *ad hoc* assumptions about the classical nature of the environment that presuppose what micro-monists like Esfeld are seeking to demonstrate. Specifically, 'decoherence theory must always make assumptions about the randomness or uncorrelatedness of the degrees of freedom' of the environment [p.16].

Since we are seeking an *independent* reason for thinking that aggregates of Bohmian particles will behave like classical objects, however, as a basis for constraining the interpretation function, an appeal to decoherence theory in this context is viciously circular. Why should we admit the possibility of only those emergent worlds in which decoherence takes place? Such a metaphysical model would have to come supplied with a reason for privileging emergent worlds comprised chiefly of sub-systems that admit approximately classical dynamics, thus reducing the set of possible worlds in which experimentalists are able to conduct their experiments to a smaller subset of physically possible worlds than the set of worlds that are consistent with the laws of Bohmian mechanics.

For micro-pluralists, the existence of classical-like behaviour is unsurprising, since 'classical' properties have a role to play in specifying the boundary conditions in which the quantum dynamics takes place. There is no universal wave function to choreograph the trajectories of all the particles, as the wave function is subject to a collapse mechanism that is 'determined top-down by the local classical context' [Drossel and Ellis, 2018, p.24]. For quantum micro-monists, like Esfeld, however, 'classical' properties have no role to play in the metaphysical model, besides the role played by physical properties in general, since the quantum dynamics is not subject to local boundary conditions. According to Esfeld, physical properties enter the metaphysical model solely through the dynamical role they play in specifying regularities in the distribution of particles. If decoherence theory cannot be relied upon to conjure classical-like worlds from the universal wave function, however, without smuggling in classical assumptions about nature, then micro-monists are reduced to appealing to the emergence of classical-like worlds as a brute constraint.

Yet even this constraint, by itself, may be too weak to overcome the radical indeterminacy of the manifest image. Whilst the set of emergent worlds might be confined to possible worlds that approximate classical (Newton-Maxwell) dynamics, it will still admit the realisation of any number of fantastic worlds, in which the objects of the manifest image follow classical mechanics, but are perceived and conceptualised in radically different ways [Paul, 2013]. It seems the necessary constraints on the manifest image, for the determined micro-monist, can only be obtained at the theoretical cost of increasingly arbitrary constraints.

ii. *Property dualism*

The second strategy I shall consider seeks to reduce the explanatory burden on quantum mechanics by restricting the type of properties determined by the wave function, embracing a form of property dualism that includes both *quantal* and *non-quantal* empirical properties. According to this approach, the properties of nature admit a certain disjointness: there are non-quantal properties that are irreducible to the positions of particles and the wave function. It is these non-quantal properties that impose additional constraints upon the manifest image.

### Phenomenal properties

A phenomenalist inspired by Russell's structuralist programme in metaphysics might conceive of this disjointness in terms of a distinction between *structural* and *intrinsic* properties [Russell, 1927]. Suppose we frame the problem of radical indeterminacy as being the problem of how scientists can *perceive* macroscopic objects, like our measuring devices, in a world made of microscopic particles choreographed by the wave function. A phenomenalist might seek to solve this problem by treating the particles as having intrinsic sensible properties, in addition to their positions. Such 'phenomenal' properties would be disjoint from any 'quantal' properties determined by the wave function, since their presence in nature would involve no change in any of the structural properties, such as the relative positions of particles, but would be correlated with changes in the intrinsic phenomenal experience of experimentalists.

The inclusion of phenomenal properties generates the possibility of *local* constraints upon the manifest image, over and above any *holistic* quantum constraints. In a phenomenalist world, the geometrical properties of objects that exist in external space and time, described in the physical language of quantum physics, might be linked with properties of sense-data in phenomenal space and time, described in terms of phenomenal language. An acceptable interpretation function, in this case, would be one which assigned a shape and size to an object in phenomenal space that corresponds to the shape and size of an object in physical space, whilst the laws of perspective would function as inter-level constraints upon the manifest image [Koons, 2017, pp.72-4]. This strategy need not require scientists to have individual particle-detectors built into their heads: it would suffice if large clusters of particles co-instantiated sensible properties, enabling scientists to perceive macroscopic objects, like the instruments they rely upon to perform their experiments.

Yet this approach comes at the theoretical cost of a kind of epiphenomenalism. By connecting the phenomenal experience of experimentalists to intrinsic properties that exist over and above any quantal properties, but make no causal difference to the structural properties of nature (namely, the positions of the particles), the phenomenalist reduces the experimentalist to a purely passive observer of a world governed by quantum mechanics. In such a world, the *observations* of experimentalists, which involve changes in intrinsic properties, seem to make no causal difference to the *actions* they perform in their experiments, which involve changes in structural properties, since for every possible world in which an experimentalist is said to perform certain actions in an experiment and make observations, there is an exact physical duplicate in which the same actions are performed but nothing is observed.

### Emergent powers

A strong emergentist might conceive the disjointness between quantal and non-quantal properties to consist instead of a division between 'higher-level' and 'lower-level' powers. In this picture, a physical system that is sufficiently large somehow attains higher-level powers that act top-down upon its basic constituents, imposing structural forces that organise their configuration according to higher-level laws [O'Connor, 1994, O'Connor and Wong, 2005]. If such properties are intrinsic to localised objects, they might impose local constraints upon the manifest image.

However, this emergentist programme also comes with theoretical costs, as I have noted (see Section 7.4). For instance, a strong emergentist account of how large systems make a causal difference to the behaviour of their basic constituents is committed to the existence of additional forces in nature, besides the four fundamental forces (namely, the gravitation force, the electromagnetic force, and the strong and weak nuclear forces), which operate according to different and more complex laws. Whilst standard concerns about the violations of mass-energy conservation entailed by this approach may not be insurmountable, we have good reason to think the strong emergentist programme over-complicates nature's laws. The quantum revolution in chemistry and thermal physics has furnished scientists with infinite quantum models of macroscopic (and mesoscopic) systems that describe thermo-chemical phenomena, which are characterised by simple laws (see Chapter 7).

## §8.5. Hierarchical constraints

All of the responses so far share a common assumption: they all accept that the manifest image of observation and experimentation is ultimately to be explained in terms of the behaviour of a single set of microscopic constituents that are governed by the same micro-physics (MM/II), apart from the exercise of hypothetical, higher-level causal powers, which may modify their behaviours under certain conditions. In the previous chapter, however, I proposed a micro-pluralist approach to nature, which rejects the radical holism that results from supposing the physical world to be characterised by a universal wave function.

A micro-pluralist conception of nature offers an alternative way of conceiving the disjointness between the quantal properties of microscopic systems and the 'classical' properties of macroscopic systems, which neither demands the existence of additional physical forces, nor collapses the practice of scientific observation into passive epiphenomenalism. According to micro-pluralists, the disjointness of certain 'classical' properties is manifest by the fact that they are not quantum-entangled, but have a role to play in specifying the *boundary conditions* in which the quantum dynamics of a system takes place. The quantal properties of nature, according to this approach, are *grounded* in ontic macroscopic systems, which have intrinsic 'classical' properties like temperature and chemical entropy. These ontic systems have distinct wave functions defined in unitarily inequivalent Hilbert space representations, and evolve according to the quantum mechanics of the DEP model.

Significantly, by recognising the context-dependence of microscopic representations of quantum mechanics, micro-pluralism rejects the micro-monist assumption that the world is an object in the universe of sets (MM/IV). According to micro-monists, a set of possible worlds $W_{\infty i}$ corresponds to a *single* semantic interpretation $I_{\infty i}$ of quantum mechanics, which describes different arrangements of the same set of microscopic constituents. According to micro-pluralists, however, the concrete potentialities of quantum systems are *jointly* determined by laws *and* their essential macroscopic states (MP/I) (see Section 7.5). It is only within the boundary conditions of a nomological machine that we can construct a set-theoretic model with a single domain of microscopic entities, $M_{\infty i} = \langle W_{\infty i}, D_{\infty i}, I_{\infty i} \rangle$.

Yet as Halvorson observes: if 'we reject that assumption' – namely, the assumption that the world is an object in the universe of sets (MM/IV) – 'Putnam's paradox simply dissolves' [Halvorson, 2019, p.268]. The problem with micro-monism is that it abstracts away from essential, macroscopic natures of physical systems, which determine the context and boundary conditions in which the micro-physics takes place. According to the micro-pluralist, however, we can think of the natures of ontic systems as imposing *local constraints* upon the manifest image, securing a world of natural kinds that are not subject to Putnam-style permutations. In Chapter 9, I shall put forward an ontology that is compatible with a micro-pluralist approach to quantum mechanics.

## §8.6. General remarks

In this chapter, I considered the Canberra plan for physics, which extends Lewis's functionalist philosophy of mind to incorporate other features of the manifest image. I discussed the claim that the manifest image is realised within a set-theoretic model of our best physics (Section 8.2), and observed how this claim becomes more doubtful in the context of quantum micro-monist ontologies, like Super-Humeanism and power monism, which remove any local constraints from the manifest image.

I advanced my case against quantum micro-monism using a Putnam-style permutation argument that leads to scepticism about reference (Section 8.3). On the one hand, it is plausible that the manifest image is constrained by local features of their environment (AI/V). On the other hand, micro-monists assume the macroscopic world of the manifest image to be realised in the structural properties of the microscopic world (MM/IV). However, quantum micro-monists, like Super-Humeans and cosmic power monists, cannot supply the necessary local constraints.

I considered some ways of tightening up the background theory to impose further constraints on the manifest image, and noted how the primitive ontology approach to quantum mechanics undermines such attempts (Section 8.4). I then considered the possibility that some properties are 'disjoint' from the quantal properties determined by the wave function, including strong emergentist and phenomenalist strategies. Finally, I suggested that local constraints arise from taking a micro-pluralist stance toward the thermodynamic limit, in which the microscopic properties of a system are grounded in macroscopic systems with essential natures (see Section 8.5). In the light of this discussion, I suggest the following desideratum to guide the construction of a more adequate metaphysical model:

*Desideratum: Macroscopic grounding constraints*
DD/VI: Other things being equal, we should favour metaphysical accounts in which the world is not an object in the universe of sets, but contains entities with intrinsic natures that impose local constraints on the manifest image.

## Notes

[1]Maudlin refers to this problem as 'Aristotle's challenge' [p.2].

[2]Personal correspondence with Esfeld.

Chapter 9

# Substantial powers

*Big fleas have little fleas upon their backs to bite 'em,*
*And little fleas have lesser fleas, and so, ad infinitum.*

– Augustus De Morgan, *Siphonaptera*

## §9.1. Beyond micro-monism

In Part II, I considered the challenge posed to classical micro-monism by the 'quantum revolution' that occurred in the 1930s and 40s (see Chapter 3), and discussed a number of metaphysical models that seek to respond it, beginning with Super-Humeanism (see Chapter 4), which adopts a primitive ontology approach to quantum mechanics, and ending with power monism, which modifies the Super-Humean model in various ways (see Chapter 6). The goal of a primitive ontology approach to quantum mechanics is to explain the empirical content of quantum mechanics in terms of statements about a primitive distribution of matter in three dimensional space (or four-dimensional spacetime). This distribution is governed by a law of nature that determines its temporal evolution.

In Part III, however, I argued that the era of quantum chemistry and quantum statistical physics, which began in the 1950s, has produced more trouble for metaphysicians who seek a realist description of the microscopic world. This trouble affects quantum micro-monist ontologies, like Super-Humeanism and power monism, which assume that the task of interpreting a physical theory is simply a matter of settling upon a single semantic interpretation of quantum mechanics, in terms of some set of fundamental microscopic constituents, and picking out their possible arrangements according to its physical laws (see Section 7.2).

Suppose we attempt to accommodate the phenomenon of quantum entanglement by adopting Bohmian mechanics and postulating a finite configuration of particles choreographed by a universal wave function, accepting the theoretical cost of denying the intrinsicality of consciousness (as argued in Section 6.4). Even so, there are thermochemical phenomena that occur at higher scales, such as phase transitions, which demand quantum models that admit physically inequivalent representations, in order to define all their states and observables (see Chapter 7). This is a problem for scientific realists who accept micro-monism, since it suggests, as Roger Jones puts it, that 'physicists don't know what deep explanatory structure of the microworld to be realists about' [Jones, 1991, p.191].

Suppose we attempt to preserve a primitive ontology of microscopic constituents that compose every physical system, by claiming that such infinite models are merely 'approximations' of the underlying microphysics, accepting the theoretical cost of reducing the explanatory power of quantum mechanics and weakening the epistemic grounds for scientific realism (as argued in Section 7.5). Even so, this will not save scientific inquiry from the radical indeterminacy of the manifest image in a holistic world with a universal wave function (see Chapter 8). This is a second problem for scientific realists who accept micro-monism, since it implies that the theory of quantum mechanics cannot be supported by observation and experimentation.

In this chapter, I aim to offer a basic outline of a *hylomorphic ontology* of quantum mechanics that incorporates both the phenomenon of quantum entanglement and thermochemical phenomena, but abandons micro-monist assumptions about nature in favour of *micro-pluralism*. In so doing, I am seeking to offer a micro-pluralist alternative to the primitive ontology approach to quantum mechanics, in which quantum states admit a hierarchical interpretation in terms of both microscopic and macroscopic properties. In order to advance beyond the primitive ontologies I have discussed so far, such as Super-Humeanism and power monism, this metaphysical model must explain how irreducible thermochemical systems arise within nature with properties like temperature and chemical entropy, and how they causally influence the evolution of each other's distributions of matter.

## §9.2. Macroscopic substances

In order to accommodate thermochemical systems such as our measuring devices, I shall introduce a set of macroscopic objects into my metaphysical model to serve as the subjects of 'classical' properties like temperature and chemical entropy (see Section 7.5). I considered earlier two different ways of introducing objects into an ontology of nature (see Section 2.3): for neo-Kantians, facts about physical objects and their properties are grounded upon facts about our preferences and practices; for neo-Aristotelians, by contrast, the physical world contains fundamental substances that exist independently of our preferences and practices, and derivative entities that are grounded in substances.

Hans Primas, for instance, seems to be taking a neo-Kantian approach to quantum mechanics in his characterisation of 'exophysics' as a perspective in which the world contains objects we can describe as open quantum systems, versus the fundamental reality of 'endophysics' in which the world consists of a closed holistic system concerning which we can make no predictions [Primas, 1990a, Primas, 1990b, Primas, 1994]. For a follower of Primas, the operation of generating exophysics from endophysics depends upon the arbitrary and selective character of our explanatory interests in choosing to attend to some features of the world rather than others. Hence the objects of scientific inquiry are not fundamental but constructed, since they ontologically depend upon our preferences and practices.

I mean to adopt a neo-Aristotelian approach instead, which draws upon Aristotle's doctrine of hylomorphism for inspiration, but deploys contemporary metaphysical tools (see Chapters 1 & 2). In tandem with Koons, I shall consider the fundamental physical entities in nature to be substances that have essential thermochemical properties. Koons proposes that the *essence* of each thermochemical substance is represented by a topology on the abstract C*-algebra that generates a concrete W*-algebra of observable properties for the whole substance, whilst the ontic states of an interacting substance are represented by normalised positive linear functionals defined on its W*-algebra (for more details, see [Koons, 2019]). For Koons, then, the appropriate representation of a quantum system is not arbitrary, but context-dependent: it depends upon the ability of scientists to distinguish what is *essential* to an ontic system from what is *accidental*.

A neo-Aristotelian approach toward thermochemical substances, in which thermochemical substances are fundamental, is not incompatible with a *restricted* neo-Kantian approach, in which there are other kinds of entities that are grounded (in part) in our preferences and practices. Nonetheless, a neo-Aristotelian approach that includes fundamental substances offers a number of advantages over an unrestricted neo-Kantian approach. As Koons points out, by ontologically committing to thermochemical substances that exist independently of our preferences and practices, it 'avoids the threat of regress or circularity that looms over Primas's picture: the experimenter, whose interests and choices determine the perspectives, must have a perspective-independent existence' [Koons, 2019]. Moreover, the decision to privilege thermochemical substances is not arbitrary, in my view, since scientific inquiry depends upon the existence of instruments that have chemical structures (see Section 7.4). Furthermore, the collapse of the wave function can be explained in terms of their chemical structures, according to Drossel and Ellis [Drossel and Ellis, 2018].

However, an ontology of nature that includes thermochemical substances faces the challenge of explaining how these transitory entities may be supposed to arise in nature. A thermochemical substance, such as a pool of water, for example, can hardly be supposed an eternal feature of nature on empirical grounds. A neo-Kantian might explain how such objects arise in terms of changes in the subjects who construct them. A neo-Aristotelian who adopts a hylomorphic approach to quantum mechanics, however, must offer an objective account of the generation and corruption of thermochemical substances in terms of the primitive ontology.

## §9.3. Power pluralism proposed

In what follows, I propose a metaphysical model called 'substance power pluralism' (power pluralism, for short), which offers a hylomorphic ontology of quantum mechanics that is compatible with the contextual quantum dynamics of the DEP model (discussed in Section 7.5). The core of this final model – the third metaphysical model that I have proposed in this thesis – subsists in five axioms:

*Substance power pluralism*

PP1: There is *power-gunk*,[1] which has the passive metaphysical power to be actualised as matter fields in which every point has a matter-density.

PP2: There are *substantial powers*,[2] which have active metaphysical powers to actualise matter fields from the power-gunk.

PP3: There are *substances*, each composed of a matter field and a substantial power, which have causal powers to change their distribution of matter-density and to 'exchange' matter-density with other substances.

PP4: Power-gunk is the substrate of *substantial change* in nature, whilst substances are subject to generation and corruption.

PP5: Substances are the substrate of *accidental change* in nature, whilst matter fields are subject to change in their distribution of matter-density.

This metaphysical model develops the primitive ontology of power monism in two significant ways: the power-atoms are replaced with 'power-gunk', and the cosmic power is replaced with a plurality of 'substantial powers'. In the exposition that follows, I shall focus on how this ontology compares and contrasts with the Super-Humean model (see Chapter 4) and the power monist model (see Chapter 6).

### i. *Matter and form*

The primitive ontology approach to quantum mechanics is motivated by the claim that there is 'something new in quantum non-locality' that calls for a break with the classical micro-monist conception of nature in which physical properties are fundamental and intrinsic features of particles (or fields) [Esfeld, 2017]. Instead, a primitive ontology approach posits the existence of a fundamental substrate of primitive matter that has 'no [intrinsic] physical properties at all', but whose spatial arrangement evolves according to a universal law of nature [Esfeld et al., 2017, p.135].

For Super-Humeans, this substrate consists of matter points: it is the distance relations between them that change (see Chapter 4). For power monists, it consists of power-atoms, which have causal powers to change their distance relations (see Chapter 6). Both Super-Humeans and power monists agree, nonetheless, that the macroscopic world is functionally realised in the microscopic world (MM/IV), which consists of a single set of microscopic constituents (MM/II). Both Super-Humeans and power monists embrace the Bohmian interpretation of quantum mechanics, in which these constituents are choreographed by a universal wave function.

In the hylomorphic ontology that I wish to propose, however, the primitive substrate of change is power-gunk, which is field-like, rather than atomic, consisting of gunky particulars that are *potentially* the matter of different substances. In addition, there are primitive substantial powers, whose manifestations carve the physical world into *actual* substances with numerically distinct 'matter fields'. The power-gunk underlies all of the matter fields, but is not identical to any of them, whilst the temporal development of each of these matter fields is context-dependent. I shall consider each of these metaphysical claims in turn.

First, power pluralism, like the GRWm model [Allori et al., 2008], embraces a gunky conception of matter to fit a stochastic modification of the Schrödinger dynamics, in which the wave function evolves according to a non-linear Schrödinger equation and is subject to spontaneous localisation. Although a 'collapse dynamics' precludes the possibility of permanent particles following continuous trajectories through space, both power pluralism and the GRWm model follow in the tradition of attributing position a privileged role in the description of nature.[3] In both models, the spread of the wave function is understood in terms of a spatially extended matter field, the probability of its localisation in terms of the matter-density in that region, and its 'collapse' as a contraction of matter-density within a region.

Secondly, power pluralism, unlike the GRWm model, does not admit the existence of a *single* distribution of matter-density, but posits a *plurality* of numerically distinct matter fields, each of which is a constituent of a distinct substance. Power pluralists reject the existence of a single matter-field, because power pluralists reject the GRW theory of the quantum dynamics, in which localisations are produced by random 'hits' on the wave function that occur universally for microscopic particles, and embrace the DEP theory instead, in which localisations depend upon 'the classical, macroscopic context' [Drossel and Ellis, 2018, pp.25]. Power pluralists deny that the 'classical context' of every quantum system can be described in terms of the same micro-physics. To obtain empirically adequate descriptions of phase transitions, for example, we require a plurality of unitarily inequivalent representations of quantum mechanics, which have different microphysical content (see Section 7.2).

Thirdly, power-gunk is not identical to any particular matter field, since power-gunk has no *actual* matter-density nor physical properties, but only the *potential* to have matter-density and physical properties. An actual matter field is elicited from the power-gunk by a substantial power, which unites itself to the matter field it elicits to compose a substance by *grounding* the causal powers of the substance (concerning this conception of metaphysical union, see Section 6.3).

Power-gunk is analogous, in this respect, to the Aristotelian-Thomistic concept of matter I described earlier (see Chapter 1), which conceives the nature of matter as *potentiality for substance*. By providing a substrate of change and the potentiality for substance, power-gunk serves as the material cause of a substance. Likewise, substantial power is analogous to the Aristotelian concept of substantial form. By uniting itself to the matter field that it elicits from the power-gunk, a substantial power acts as the formal cause of a substance, conferring an essential physical nature upon the substance as a whole. According to power pluralism, it is the *essence* of a physical substance, together with its local environment, that determines the particular *context* in which the context-dependent micro-physics takes place.

Power pluralism thus endorses a type of *plurality hylomorphism*, in which the matter and form of a substance are numerically distinct from one another, but compose a metaphysical unity (see Section 6.3). The power-gunk underlying the matter field of a substance is not *nothing*, nor is it part of a noumenal realm of which we can *say* nothing, nor does it derive its being from the *subjective* act of abstracting it from a substance. In this model, the physical matter fields of two substances are distinct from one another in virtue of the prior distinctness of the two parcels of metaphysical power-gunk that they actualise.[4] The nature and number of the substances are thus constrained in two ways: first, the substantial powers fix for all time the repertoire of potential substances; secondly, the power-gunk imposes a restriction on the total quantity of matter-density that is actualised at a given moment. Together, the power-gunk and the substantial powers ground all of the primordial possibilities of quantum mechanics (see Section 7.3).

### ii. *Substances and entities*

A primitive ontology approach to quantum mechanics seeks to account for the measurement outcomes of scientific experiments, such as the EPR experiment (see Section 3.2), and more generally the macroscopic objects upon which scientists depend, by offering an account of the empirical content of a physical theory that is exhausted by its statements about the primitive ontology [Maudlin, 2019]. A Stern-Gerlach device, for example, is observed to register ‘spin-up’ or ‘spin-down’ in an EPR experiment because it contains a parcel of matter arranged pointer-wise in space.

In the world of Super-Humeanism or power monism, the only object in nature that may be said to have properties independently of any other object is the cosmos itself, which is a single substance with a finite number of integral parts. For Super-Humeans, the integral parts are matter points, which are holistically individuated by the distance relations in which they stand. For power monists, the integral parts are power-atoms, whose powers are grounded in the power of the cosmos as a whole. Both metaphysical models imply that the causal profiles of any macroscopic objects of scientific inquiry must be *extrinsic* to them, since such objects are composed merely of integral parts of the cosmic substance (see Section 6.4).

Similarly, in the hylomorphic ontology I wish to propose, the empirical content of a physical theory is exhausted by its statements about the matter fields of fundamental substances. However, the macroscopic instruments upon which scientists depend to perform their experiments must have chemical structures that instantiate properties like solidity, so they can be picked up and manipulated, and manifest distinct colour profiles, so they can be distinguished visually from their surroundings. In power pluralism, the thermochemical properties of macroscopic (or mesoscopic) entities, which explain their solidity and colourfulness, are irreducible to the microphysical properties of any finite set of microscopic constituents (see Section 7.5). In fact, different quantum systems have different 'classical' properties, like temperature and chemical entropy, which are not quantum-entangled with one another, and these systems are distinguished from one another in an experiment by isolating their thermochemical powers.

Power pluralists thus reject the cosmic holism of Super-Humeanism and power monism, which leads to the radical underdetermination of the manifest image (as argued in Chapter 8). They also reject the claim that any macroscopic object or spatiotemporal region must have all of their causal profiles extrinsically, which leads to the expulsion of intrinsic consciousness from the physical world (as argued in Section 6.4). Both of these problems can be avoided, and the role of 'classical' properties in fixing the context of the quantum dynamics affirmed, by taking a *micro-pluralist* stance to the thermodynamic limit, in which the microscopic properties of a physical system are grounded in its essential macroscopic (or mesoscopic) state (defined in Section 7.5).

Following Koons, power pluralists embrace *substance pluralism*, regarding macroscopic (or mesoscopic) thermochemical substances as the fundamental building blocks of the physical world [Koons, 2019]. They are fundamental in the sense that there is no change in the physical world that does involve change in a thermochemical substance, in accordance with Schaffer's 'tiling constraint' [Schaffer, 2010]. The thermochemical *essence* of a substance, Koons suggests, is represented in $QM_\infty$ by a topology on the abstract C*-algebra that generates a concrete W*-algebra of observable properties for the whole substance. The matter of these substances support global, macroscopic observables that do not enter into quantum superpositions: they are not merely swarms of particles, but have metastable chemical structures, which are not quantum-entangled with their environment. According to this model, these substances have intrinsic thermochemical properties that are metaphysically grounded in the substance as a whole. It is only the quantal properties of their microscopic parts that are quantum-entangled with one another.

Power pluralists thus conceive the world as the domain of multiple substances of different physical scales. These substances are not necessary or permanent entities that exist without further explanation, but contingent hylomorphic composites that are subject to generation and corruption. When a substantial power elicits a matter field from the power-gunk, it unites itself to the matter field that it elicits by being the formal cause of a substance with an essential physical nature. This composite is a robustly Aristotelian substance (FS/IV-V), since the physical parts of the substance depend for their natures upon the whole of which they are part, and it has active and passive causal powers (of which more presently). When a substantial power ceases to elicit the matter field of the substance from the power-gunk, it ceases to unite itself to the matter of the substance, and the substance ceases to exist.

Not every entity in nature is a substance, however, and substantial powers do not actualise substances at all physical scales. For instance, we have good reason to reject microscopic particles as substances: the EPR correlations between local observables in quantum mechanics suggest that particles lack intrinsic physical properties, but are interdependent entities that belong to a larger whole (see Chapter 3). There are also physical and metaphysical considerations for rejecting the claim that there is only one cosmic substance. First, it seems to be possible to isolate thermochemical systems in nature with 'classical' properties that are not quantum-entangled (see Chapter 7). Secondly, the manifest image would be radically underdetermined if cosmic holism were true, and the theory of quantum mechanics would be empirically empty (see Chapter 8). Contrary to micro-monism, which claims that the macroscopic world is composed of the integral parts of a cosmic whole, which persist through all forms of change, power pluralism conceives of microscopic entities as being integral or potential parts of macroscopic (or mesoscopic) substances, whose physical properties are grounded in the substances of which they are parts.

### iii. *Laws and powers*

In the primitive ontology approach to quantum mechanics, the matter composing any object of scientific inquiry evolves according to a law of nature, whilst the wave function enters this metaphysical account through the nomological role that it plays in the temporal development of the matter. There are two principle ways of spelling out the notion that the wave function is nomological: namely, by appealing to some form of Humeanism, such as the 'best systems' account of laws, or to some form of powerism, in which laws are grounded in powers [Esfeld et al., 2017].

Similarly, in this hylomorphic approach to quantum mechanics, the wave function plays a nomological role in describing the temporal evolution of a matter field. Like the power monist, the power pluralist adopts a powerist conception of laws, and distinguishes *causal laws* that connect causes to effects from *metaphysical laws* that connect grounds to what is grounded (see Chapter 6). Power pluralists think of the Schrödinger equation as a metaphysical law that concerns a grounding relation. Unlike the power monist, however, the power pluralist adopts the DEP model of the quantum dynamics, rather than the Bohmian theory, and posits the existence of numerically distinct matter fields.

According to power pluralism, the metaphysical grounding relation that concerns the modified Schrödinger equation holds between the powers of a matter field and the substantial power. In this model, there are thermochemical substances in nature, each of which is composed of a matter field and a substantial power. Every substance has an intrinsic power to change the distribution of matter-density in its matter field, as well as active and passive causal powers to 'exchange' matter-density with the matter fields of other substances. These powers are grounded *bottom-up* in the power-gunk, from which the matter field is elicited, and *top-down* in the substantial power, which elicits the matter field of the substance. They change with time according to the quantum dynamics of the DEP model.

I suggest that the bottom-up component of their grounding is described by the *linear* part of the quantum dynamics, which is shared in common with every matter field that is elicited from the power-gunk. I propose that the top-down component of their grounding is described by the *non-linear* part of the quantum dynamics, which is peculiar to the 'classical context' of the particular substance (see Appendix C).[5] For power pluralists, the continual evolution of the matter field of a substance is the manifestation of its *first-order power* to change its matter-density distribution, whereas the stochastic localisation of the matter field is a manifestation of their *second-order powers* to 'exchange' matter-density between their matter fields, by changing their first-order powers. We may think of the continual change in the matter-density of a matter field as involving both *formal* and *efficient* causation (see Section 1.3), and thus involving the exercise of substantial and causal powers.

To see this, consider the case of a transfer of matter-density between the matter fields of two substances through the exercise of their second-order powers. This may take place, for example, when a particle from the matter field of a substance $\chi$, such as a photon, becomes part of the matter field of a measuring instrument $\xi$, such as a photon detector, which registers this event with a characteristic 'click'. (For simplicity, I am treating the photon detector as a substance, rather than an aggregate.) This 'exchange' of matter-density between $\chi$ and $\xi$ is only made possible, however, by the substantial power of $\xi$ eliciting more matter-density from the power-gunk, and the substantial power of $\chi$ eliciting correspondingly less. This in turn requires a change in the first-order powers of both substances that change the matter density distribution of their respective matter fields.

In the case of the measurement of a particle from a matter field $\chi$, the local environment of $\chi$ will include a macroscopic instrument $\xi$ with a metastable chemical structure, a finite temperature, and an intrinsic heat bath characterised by infinite degrees of freedom. As Drossel and Ellis argue: 'At the micro level, the context for the interaction is set by a specific metastable structure that allows transitions upon impact of the particle that is to be detected' [Drossel and Ellis, 2018, p.19]. We may think of this structure as being sustained by the substantial power of $\xi$. The top-down influence of the causal powers of $\xi$ upon the matter field of $\chi$ is reflected in the formalism by the evolving external potential imposed upon the wave function by the thermal properties of $\xi$ [p.17] (which are not defined in the Hilbert space in which the wave function of $\chi$ is defined).

We may think of the matter field equation (borrowed from the GRWm model), as describing the manifestation of the first-order power of a substance to change the distribution of matter density $m^{\psi}(x,t)$ in its matter field (see Appendix C). This power is grounded in the substantial power of the substance, and is subject to change in accordance with the metaphysical law that describes the grounding relation between the substantial power and the powers of the substance. The matter field of the substance at time $t$, and its matter field at time $t' > t$, are united as the temporal parts of a single substance in virtue of this *metaphysical law*, which links all the potential distributions of matter density elicited by the substantial power (cf. Section 6.3). The substantial power is thus the principle of unity of the substance.

### iv. *Microscopic and macroscopic properties*

In the primitive ontology approach to quantum mechanics, the primitive matter of which all physical systems are composed lacks any intrinsic physical properties. The properties that feature in any physical theory that describes interactions between different sub-systems enter into the metaphysical account solely through the dynamical role they play in describing local regularities in the distribution of matter. For Super-Humeans and power monists, who adopt the Bohmian interpretation of quantum mechanics, physical properties like mass and charge are neither intrinsic properties of microscopic systems nor elements of the primitive ontology.

However, in the hylomorphic alternative I am proposing, certain macroscopic 'classical' properties have an additional role to play in fixing the *boundary conditions* in which the quantum dynamics takes place, as described in the DEP model (see Section 7.5). This *physical disjointness* between the quantal and 'classical' properties of a system allows us to accommodate the emergence of thermochemical phenomena in macroscopic systems, like phase transitions. Nonetheless, power pluralists are able to offer a *metaphysically unified* approach to quantum mechanics by adopting a hierarchical interpretation of the quantum state, in which a Hilbert space corresponds to the (essential) macrostate of a quantum system, whilst a vector that is defined in this Hilbert space corresponds to its (accidental) microstate [Sewell, 2014, pp.4-5]. In so doing, the power pluralist rejects the quantum micro-monist claim that the physical world, as a whole, is characterised by a universal wave function, but does not reject the requirements of scientific realism (AI/I-V).

The universal wave function that features in the Bohmian interpretation of quantum mechanics, for instance, is a projection of a vector defined in a single Hilbert space onto the finite configuration space of $N$ quantum particles. This wave function determines the quantal properties of the particle system that can be measured in an experiment. However, as I argued in Chapter 7, there is more information in the hierarchical quantum state of an infinite quantum system. The quantum mechanics of infinite systems, $QM_\infty$, makes available an 'operator topology' that defines the convergence of infinite sequences of quantum operators, which permits a core of 'classical', macroscopic observables to be defined that characterise the system's essential macrostate.

The fact that an ontic system has certain macroscopic, 'classical' properties, in addition to the quantal properties of the system of particles with which it is associated, implies there is more to being a matter field than the way in which it relates to space and time in a quantum experiment. A quantum experiment involves a finite number of microscopic measurements, in which a system relates to the measuring device as a set of *discrete quanta*, such as photons that register with a 'click' in a photon detector. For power pluralists, however, matter also *cooperates as a continuum* in a plurality of different ways. This peculiarity is reflected in the formalism, I suggest, inasmuch as two wave functions, $\psi \in \mathcal{H}_1$ and $\phi \in \mathcal{H}_2$, which characterise two distinct matter fields, may determine identical distributions of matter-density, $m^\psi(x,t) = m^\phi(x,t)$, yet belong to unitarily inequivalent Hilbert spaces. These distinct Hilbert space representations may support disjoint sets of macroscopic observables in the continuum limit. It is because matter composes in a plurality of ways – as many, I suggest, as the number of kinds of substantial powers – that substances have such 'classical' properties as temperature and chemical entropy.

A themochemical substance, however, is not exhausted by its physical characterisation. On the one hand, the second-order powers of a substance to 'exchange' matter-density with other substances are *physical* powers that can be isolated in an experiment. Their role is reflected in the 'boundary conditions' that are imposed upon the evolution of a quantum system via the feedback loop in the DEP model. On the other hand, the first-order power of a substance to change its distribution of matter-density is a *metaphysical* power of self-regulation, and this distribution of matter-density cannot be measured directly. It is not possible to measure the quantal properties of a system without significantly disturbing them, since any measurement of any part of a quantum system will involve a localisation in the wave function of the system as a whole. Whilst it is the second-order powers of a substance, which are not quantum-entangled with its environment, that make quantum systems empirically distinguishable from one another, the physical powers of a substance to 'exchange' matter-density with other substances are unintelligible apart from the metaphysical powers of substances to change their distributions of matter-density.

v. *Accidental and substantial change*

In the primitive ontology approach to quantum mechanics, all change in the physical world consists of the change in the spatial distribution of matter. There is one way that the world is at a given moment (specified by its arrangement of matter) and there is one set of ways in which it might be (consisting of its possible arrangements of matter). For micro-monists, like Super-Humeans or power monists, the world is conceived as a single nomological machine, and all change is determined by its laws.

In the hylomorphic approach I am advancing, by contrast, 'there's a single way the world is, but ...there isn't a single set of ways it might be' [Ruetsche, 2011, p.353]. Power pluralists reject micro-monism, and its unimodal conception of physical possibility (MM/III), because thermochemical phenomena cannot be adequately represented in a single microscopic state space (see Chapter 7). They adopt a micro-pluralist interpretation of quantum mechanics, in which the world consists of different kinds of nomological machines that are modelled using physically inequivalent representations. For example, when a quantum system undergoes a phase transition, such as a ferromagnet that experiences spontaneous magnetisation, it composes a different nomological machine, $W_{\infty i} \to W_{\infty j}$, in which one set of observables and dynamics, defined in an appropriate Hilbert space, are discontinuously replaced by another set of observables and dynamics, defined in a unitarily inequivalent Hilbert space. This change is not determined by its laws (see Chapter 7).

According to power pluralists, there is both accidental and substantial change in nature. *Accidental change* occurs with the exchange of matter-density between substances, and the change in the distribution of matter density in their respective matter fields. It is the accidents of the substances that change. *Substantial change* takes place, however, when a substantial power begins or ceases to elicit a matter field from the power-gunk. This change is heralded by the emergence of novel thermochemical phenomena, such as phase transitions, in which one substance is succeeded by a numerically distinct substance with different causal powers. A substance may thus be said to have both an accidental and a substantial form (cf. Chapter 1). Its *accidental form* is represented by a wave function $\psi$, which is determined in part by its interactions with other substances through the feed-back mechanism described by Drossel and Ellis. The *substantial form* of the substance is represented by the Hilbert space $\mathcal{H}$ in which this wave function is defined, $\psi \in \mathcal{H}$.

## §9.4. Advantages of power pluralism

By replacing the power-atoms of power monism with power-gunk, and enriching the primitive ontology to include substantial powers, power pluralism gains a number of advantages over rival models, such as Super-Humeanism and power monism.

First, power pluralism is able to solve the problem of extrinsicality, which is the problem of accommodating the intrinsicality of consciousness in a world governed by quantum mechanics (see Chapter 6). This problem arises for primitive ontology approaches to quantum mechanics because it is plausible that a macroscopic entity with intrinsic consciousness has an intrinsic causal profile, yet a quantum-entangled world seems to be a world in which no macroscopic entity has an intrinsic causal profile. Power pluralism is able to solve this problem, however, because it supports an ontology of thermochemical substances, which are not quantum-entangled with their environments. These substances have intrinsic causal profiles in virtue of their possessing essential casual powers (DD/III). (Like Koons, I shall regard an organic entity to be a type of thermochemical substance.)

Secondly, power pluralism is able to solve the problem of emergence (see Chapter 7), which is the problem of explaining thermochemical phenomena in macroscopic quantum systems in terms of the states and observables of microscopic systems. This problem arises for primitive ontology approaches to quantum mechanics because they conceive the world as a finite quantum system with a single wave function, whilst these states and observables are only defined for infinite quantum systems that have irreducible boundary conditions. Power pluralism is able to solve this problem, however, because it rejects micro-monist interpretations of quantum mechanics, which posit a finite set of microscopic constituents that evolve within a single microscopic state space, and adopts a micro-pluralist conception of quantum mechanics, in which different systems may evolve in unitarily inequivalent state spaces (DD/IV). According to power pluralists, the fundamental building-blocks of reality are substances with intrinsic thermochemical properties.

Thirdly, power pluralism is able to circumvent the problem of radical indeterminacy, which is the problem of explaining how the scientific image can have empirical content when the manifest image is radically underdetermined by the microscopic quantum world (see Chapter 8). This problem affects primitive ontology approaches to quantum mechanics because the content of the manifest image must be constrained by local features of the environment (to avoid Putnam-style permutation arguments that lead to scepticism about reference), but a world made of matter without physical properties lacks any such constraints. Power pluralism is able to circumvent this problem, however, since it does not require the manifest image to be functionally realised by the microscopic world (MM/IV). According to power pluralists, we can think of the intrinsic natures of fundamental substances as imposing local constraints on the manifest image (DD/V).

## §9.5. Arguments from naturalism

This outline of my new ontology is doubtless subject to many points of clarification, and will require further development. One substantial objection that I should like to anticipate, however, is the claim that it is not sufficiently *naturalistic*. I shall consider two ways of forming this objection, which I shall then refute. The first line of attack takes a Quinean-Lewisan stance that might be formulated as follows:

*Argument from naturalism (I):*

i. If naturalism is true, then every entity in the ontology must be a referent of one of our best scientific theories.

ii. If power pluralism is true, then at least *some* of the entities in the ontology are not referents of *any* of our best scientific theories.

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iii. Therefore, if naturalism is true, power pluralism is false (by i. and ii.).

I take the first premise to be motivated by something like Quine's famous dictum: 'to be is to be the value of a variable' [Quine, 1948]. The elements of a naturalistic ontology, according to this recipe, must be restricted to those entities over which our 'best theories' quantify (once they are properly interpreted). Our best theories are conceived as those theories that are most successful in explaining natural phenomena. The second premise may be advanced by pointing out that the elements in the primitive ontology of power pluralism are not the referents of *any* physical theory. The conclusion follows from the premises: for type-I naturalists, this failure of reference must disqualify such elements from being members of a natural ontology.

Nonetheless, I think such strictures are misguided. Following Ruetsche, I have argued that $QM_\infty$ requires *two* stages in its interpretation to enable its explanatory power: the first-stage is universal and pertains to the *potential* states and observables of every system in nature, but it does not explain what scientists actually observe. The second-stage refers to *actual* entities and pertains to what scientists actually observe, yet there are a plurality of ways of offering second-stage interpretations and the truthfulness of their content is *context-dependent*. The suggestion that nothing belongs in nature besides those things that appear as the referents of a successful physical theory amounts to the demand for a single second-stage interpretation of quantum mechanics. This requirement, however, impairs the explanatory power of quantum mechanics, which admits multiple semantic interpretations, and in so doing undermines the assumption of realism (see Chapter 7).

I think we should reject the first premise as scientifically outmoded: the Quinean-Lewisan tradition misconceives the unity of nature, conflating primodial and physical possibilities and mistaking the natural world for a single nomological machine. I have argued that this leads to the radical underdetermination of the manifest image (see Chapter 8). This first line of attack, then, reflects an idealised conception of physics that does not reflect scientific practice. A second line of attack might be advanced, however, in the spirit of the Stanford School of the philosophy of science, which offers a rival perspective on nature to the Quinean-Lewisan tradition. It could be formulated as follows:

*Argument from naturalism (II):*

i. If naturalism is true, then it is possible in principle to manipulate the causes of *all* natural phenomena (in an appropriate scientific experiment).

ii. If power pluralism is true, then it is not possible even in principle to manipulate the causes of *some* natural phenomena.

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iii. Therefore, if naturalism is true, power pluralism is false (by i. and ii.).

I take the first premise of this argument to be motivated by something like Hacking's principle that what is *real* is what we can *manipulate* [Hacking, 1983]. A naturalistic ontology, from this standpoint, should restrict itself to explanations involving entities that we have some reasonable hope of isolating within a scientific practice. I take the second premise as following from the power pluralist's commitment to entities like substantial powers, which are the metaphysical grounds of substances' causal powers to bring about natural phenomena, but do not themselves exist within the theatre of space and time. The conclusion follows from the premises: type-II naturalists cannot consistently affirm naturalism and power pluralism.

Again, I find such worries to be misplaced. The fact that we cannot isolate substantial powers in a scientific experiment does not prevent us from *abstracting* them from the various substances with which we are in causal contact, in virtue of the causal powers that substantial powers ground. In fact, this is the same kind of conceptual operation in which physicists are engaged when they take the continuum limit. In taking this limit, certain global observables supported by thermochemical systems are abstracted from the quantum-entangled local observables of their infinite sub-systems. The practice of 'abstracting' is a necessary conceptual operation for producing interpretations of theories that have empirical content.

I think we should reject the first premise of the second argument by restricting Hacking's principle to the domain of substances that have causal powers. It should not be applied to the primitive ontology of power pluralism, which supplies the *metaphysical grounds* of their causal powers. The Stanford School has exaggerated the disunity of nature by rejecting the possibility of a *metaphysically unified* account of nature. On the one hand, it is true that nature is not a single nomological machine that is described by the laws of our best physics. On the other hand, it is possible to provide a unified description of nature in terms of the *potentialities* of physical substances, by adopting a two-stage interpretation of quantum mechanics, and embracing a distinction between causal and metaphysical laws.

In short, I think there is good reason to reject the metaphysical scruples of both type-I and type-II naturalists. Type-I naturalists are attached to an antiquated metaphysical conception of nature, whilst type-II naturalists are unduly shy of metaphysics. By adopting a hylomorphic conception of nature, however, in which substances are composed of both matter (power-gunk) and form (substantial power), power pluralism is able to distinguish and hold in balance the (metaphysical) unity and the (physical) disunity of nature, avoiding the extremes of both the Quinean-Lewisan metaphysical tradition and the Stanford School of philosophy of science.

## §9.6. Final remarks

In this final chapter, I have proposed a neo-Aristotelian ontology called power pluralism, which both accommodates the phenomenon of quantum entanglement and the emergence of quantum systems with thermochemical properties. I advanced a 'micro-pluralist' approach to quantum mechanics in which quantum states are ontic states of macroscopic substances that have intrinsic thermochemical properties (see Section 9.2). In order to explain how these substances are generated, and how their quantal and thermochemical properties evolve according to physical laws, I outlined a new hylomorphic ontology of quantum mechanics (Section 9.3), which consists of power-gunk and substantial powers. According to this micro-pluralist model, the world is not composed of microscopic constituents. Rather, macroscopic (or mesoscopic) thermochemical substances are elicited from a substrate of power-gunk by substantial powers, which belong to distinct natural kinds. I argued that this model offers a number of advantages over rival primitive ontologies (Section 9.4): it accommodates the intrinsicality of consciousness, it explains the emergence of thermochemical phenomena, and it circumvents the problem of radical indeterminacy. Finally, I anticipated the objection that this model is insufficiently naturalistic, and suggested how power pluralism offers a *via media* between the Quinean-Lewian metaphysical tradition and the Standford School that neither exaggerates nor denies the unity of nature (Section 9.5).

## Notes

[1]The term 'power gunk' was coined by Marmodoro in [Marmodoro, 2015].

[2]The term 'substantial power' was coined by Marmodoro to denote a power that is a holistic unity consisting of 're-individuated' basic microphysical powers [Marmodoro, 2017]. The substantial powers in power pluralism generate substances in a different way, since there are no basic microphysical powers for them to re-individuate.

[3]As Ghirardi and his collaborators argued: 'This is quite natural since the definiteness, the particularity of the world of our experience, derives from our perceiving physical objects in definite places, and this is also why the prescriptions for establishing the psychophysical correspondence usually involve positions' [Ghirardi et al., 1995, p.6].

[4]Power-gunk is thus close to the scholastic concept of 'prime matter', whilst matter fields are close to the notion of 'designated' matter.

[5]Or, at least, any non-linear terms that cannot be got rid of by nonlinear field redefinitions.

# Part IV

# End matter

# Appendices

## §*A*. The de Broglie-Bohm pilot-wave theory

To derive de Broglie's version of the 'Bohmian law of motion', which describes the velocities of a particle configuration, let us begin with the time-dependent Schrödinger equation of quantum mechanics:

$$i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi,$$

where $\psi$ is a wave function defined in an $N$-dimensional configuration space, $\psi = \psi(\mathbf{Q}_i, \ldots, \mathbf{Q}_N, t)$, and $H$ is the standard non-relativistic Hamiltonian (in this case, for spinless particles):

$$\hat{H} = \left(-\sum_{i=1}^{N}\frac{\hbar^2}{2m_i}\nabla_i^2 + V\right).$$

We may think of the wave function as a 'probability fluid' that is flowing through physical space with a current:

$$\mathbf{j} = \frac{i\hbar}{2m}\left(\psi\nabla\psi^* - \psi^*\nabla\psi\right) = \frac{\hbar}{m}Im(\psi^*\nabla\psi).$$

The current satisfies a continuity equation,

$$\frac{\partial\rho}{\partial t} + \nabla.\mathbf{j} = 0 \implies \frac{\partial}{\partial t}\int_V |\psi|^2 dV + \int_S \mathbf{J}.d\mathbf{A} = 0,$$

where the density $\rho = |\psi|^2$. The continuity equation imposes a conservation law upon the probability density, $\rho$, in which the rate of change of the probability of a particle being measured in some volume $V$ is equal to the rate at which probability flows into $V$.

De Broglie proposed taking the wave function as a pilot-wave that supports a configuration of particles $\mathbf{Q}_i(t)$, which have definite positions at all times. He hypothesised that the trajectories of the particles could be deduced from the probability current density, where the velocity is the ratio of the probability current $\mathbf{j}$ to the probability density $\rho$:

$$\frac{d\mathbf{Q}_i}{dt} = \frac{\mathbf{j}}{|\psi|^2}.$$

The Bohmian equation of motion for the particles is thus of the form:

$$\frac{d\mathbf{Q}_i}{dt} = v_i^{\psi}(\mathbf{Q}_1, ..., \mathbf{Q}_N) \propto Im \frac{\psi \nabla_i \psi}{|\psi|^2}$$

The equation of motion can be expressed more concisely by expressing the wave function in the form $\psi = |\psi| \exp(iS/\hbar)$, where $S$ is the phase of the wave function:

$$m_i \frac{d\mathbf{Q}_i}{dt} = \nabla_i S.$$

In the picture this affords, the Bohmian particles are driven by the pilot wave along trajectories that are perpendicular to surfaces of constant phase. For further details, consult [Dürr, 2009] and [Allori et al., 2008].

## §$B$. The GRW universal collapse theory

In the GRW theory, proposed by Ghirardi, Rimini and Weber [Ghirardi et al., 1986], a physical system is also assigned an $N$ particle wave function that solves the time-dependent Schrödinger equation, $\psi = \psi(\mathbf{Q}_i, \ldots, \mathbf{Q}_N, t)$, where $\mathbf{Q}_i \in \mathbb{R}^3$ and $i = 1 \ldots N$.[6] The wave function, however, is subject to collapse. For any every $x$ in $\mathbb{R}^3$ we define a 'collapse operator',

$$\Lambda_i(x) = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left( -\frac{(\hat{Q} - x)^2}{2\sigma^2} \right),$$

where $\hat{Q}_i$ is the position operator of the particle $i$, and $\sigma$ is a constant of nature. The evolution of the wave can be decomposed into two parts. First, it evolves unitarily according to the Schrödinger equation, from time $t_0$ until some random time $T$, such that $\psi(t) = U_{\Delta T} \psi(t_0)$ for $t \in [t_0, T]$, where $U_t = \exp(-i/\hbar \hat{H})$. Secondly, at time $t = T$, the wave function undergoes spontaneous collapse:

$$\psi_T \to \psi_{T+} = \frac{\Lambda_I(X)^{1/2}\, \psi_T}{||\Lambda_I(X)^{1/2}\, \psi_T||},$$

were $I$ is from the set of $N$ particles, $\{1, \ldots, N\}$, chosen randomly with uniform probability density, and $X$ is the centre of the collapse, chosen randomly with non-uniform probability density:

$$P(X \in dx | \psi_T, I = i) = \langle \psi_T | \Lambda_i(x) \psi_T \rangle \, dx.$$

The algorithm is then reiterated for $\psi_{T+}$, which experiences a period of unitary evolution, before undergoing spontaneous collapse. For further details, consult [Ghirardi et al., 1986] and [Allori et al., 2008]. In GRWm theory, proposed in [Ghirardi et al., 1995], the Schrödinger equation and the collapse dynamics are supplemented by a field equation, which is of the form:

$$m(x,t) = \sum_{i=1}^{N} m_i \int_{R^{3N}} dq_1 \cdots dq_N \delta(q_i - x) |\psi(q_1, \cdots, q_N, t)|^2.$$

The field $m(x,t)$ is understood to be the density of 'matter' in space at time $t$, where each point $x$ in the matter field receives a mass-weighted contribution from each 'particle' (or $i$th degree of freedom), $i = 1, \ldots, N$, by obtaining a marginal distribution for each particle $i$ (at $q_i = x$) from the probability density $|\psi|^2$. The matter field is not particle-like but continuous.

## §*C*. The DEP contextual collapse theory

The DEP theory, as I call it – after Drossel, Ellis and Primas – offers an alternative model of wave function collapse, in which the interaction of a quantum system with the intrinsic heat bath of a measuring instrument plays a key role in solving the measurement problem [Drossel and Ellis, 2018] (cf. [Primas, 1990a, Primas, 1990b]). I do not propose to discuss any part of it in detail here, but merely to note that the collapse of the wave function is achieved via a feedback loop, which depends upon the local environment. Consider the Schrödinger equation for an electron:

$$i\hbar \frac{\partial \psi}{\partial t} = (T + V)\psi,$$

where the potential is due to the external environment. In the case of an environment that includes a detector, the potential is formed by the ions composing the lattice of the detector material. However, the potential in which the wave function of the electron evolves changes, because it depends on the electron charge density:

$$\frac{\partial V(\mathbf{x})}{\partial t} = f(\mathbf{x}, |\psi|^2)$$

By integrating and inserting the above into the Schrödinger equation, we obtain:

$$i\hbar \frac{\partial \psi}{\partial t} = \left( T + \int_{-\infty}^{t} dt' f(\mathbf{x}, |\psi(t')|^2) \right) \psi.$$

This is a non-linear Schrödinger equation. Since the feedback loop involves the heat bath of the detector, which cannot be described by a process of unitary evolution in this model, localisations of the wave function can be obtained.

# List of Assumptions of Inquiry



# List of Desiderata



# List of Propositions

# List of Primitive Ontologies

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